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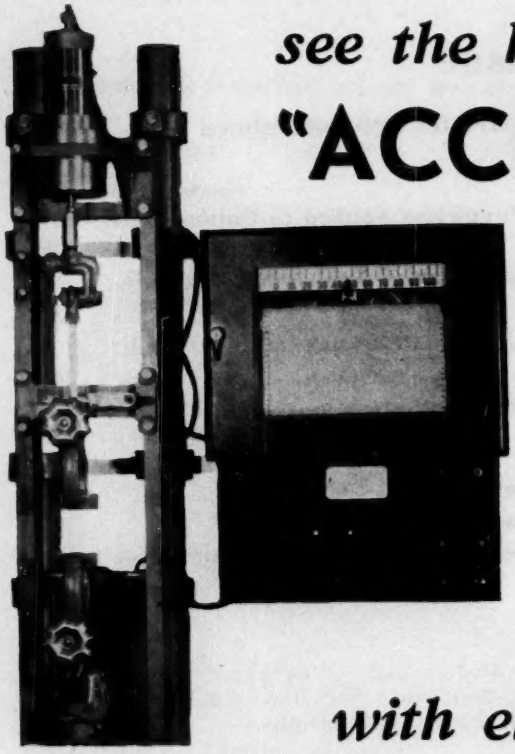

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TEXTILE RESEARCH JOURNAL

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Resistance to Microbiological Deterioration of Resin-Treated Cellulosic Fabrics

T. F. Cooke

American Cyanamid Company, Bound Brook, N. J.

Introduction

It has been found that textile resins of the water soluble, aminoplast type will prevent the microbiological deterioration of cellulosic fabrics. In order to have a better understanding of this subject, the following points are discussed: (*1*) the physical and chemical structure of cellulosic fibers, (*2*) the types of microorganisms that attack cellulose, (*3*) the fungicides and bactericides normally used to prevent microbiological deterioration of cellulose, and (*4*) some chemical reactions with cellulose that alter its resistance to microbial decomposition. Then the effect of textile resins on (*1*) the properties of cellulosic fabrics and (*2*) the microbiological deterioration of fabrics, is discussed.

Structure of Cellulosic Fibers

Chemical

The main constituent of cellulosic fibers is, of course, cellulose. However, a typical cotton fiber, according to Guthrie *et al.* [20] contains 6% of other ingredients. Its chemical composition is given in Table I.

TABLE I. CHEMICAL COMPOSITION OF TYPICAL COTTON FIBER

Constituent	(%)
Cellulose	94
Protein	1.3
Ash	1.2
Pectin	0.9
Organic acids	0.8
Waxes	0.6
Sugars	0.3
Others	0.9

Cellulose is generally considered to be predominantly composed of anhydroglucose units linked together through an ether group. The chemical formula can be written as $(C_6H_{10}O_5)_x$, where x represents the number of anhydroglucose units in the molecule or the degree of polymerization. In cotton fibers, the average value of x is 3000 (molecular weight of 486,000) or greater and may be as high as 8000 to 10,000 (molecular weight of 1,300,000 to 1,620,000) [18, 23]. Viscose rayon has a lower average value of x of 200 to 600 (molecular weight of 32,000 to 97,000).

The formula for cellulose in more detail, showing a cellobiose unit, which consists of two anhydroglucose units linked together, is shown in Figure 1.

Cellulose contains a small percentage of carboxyl groups which are located at the no. 6 position in the anhydroglucose molecule [38]. There is a possibility that cross linking between cellulose chains

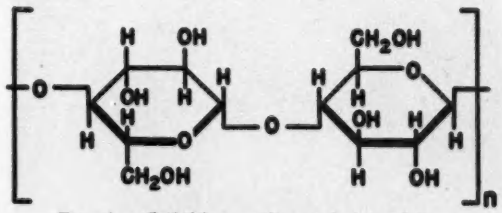

FIG. 1. *Cellobiose unit consisting of two anhydroglucose units linked together.*

TABLE II. DIMENSIONS OF AVERAGE COTTON FIBER AND CONSTITUENTS

	Length	Width
Fiber	3 cm.	30 μ
Fibril	230 μ	0.3 μ
Micelle	600 Å.	65 Å.
Cellulose molecule	20,000 Å.	7.5 Å.
Anhydroglucose unit	5.2 Å.	7.5 Å.
Carbon atom	1.5 Å.	1.5 Å.

occurs because of ester formation between the carboxyl groups and hydroxyl groups of adjacent cellulose chains. According to Pacsu *et al.*, there is also a possibility of cross linking occuring through hemiacetal groups to the extent of 0.3% [24, 35]. Any cross linking by primary valence bonds, if it occurs, is not extensive, most of cellulose being a long, linear chain of glucose molecules.

Physical

The dimensions of the average cotton fiber and its constituents are given in Table II.

The fiber is composed of three main parts, the outer primary wall, the secondary wall, and the lumen. The primary wall or cuticle is very thin and is composed of a loose network of strands of cellulose mixed with waxes and pectin. The secondary wall is the major part of the cotton fiber and is composed of a large number of cellulosic threads or fibrils arranged in a random fashion along the longitudinal axis of the fiber. The rings in cellulose which are the result of the difference between night and day growth may be likened to the summer–winter rings in wood. A photomicrograph of the fibril structure obtained by disintegrating cotton fibers by wet-beating in a Waring Blendor [25] is given in Figure 2. These fibrils are estimated to be 0.25 to 0.5 microns in diameter [13, 15, 22]. The lumen, which is the center portion of the fiber, is very thin and, with mature fibers, is almost invisible. Intermediate in size between the fibrils and the anhydroglucose units are the so-called "micelles" or aggregates of anhydroglucose or cellobiose units. These micelles have been described as similar to bricks in a wall which overlap each other and are held together by cementing substances (waxes, pectins, etc.) [14, 21, 42].

FIG. 2. *Fibril structure of cotton fiber.*

Cellulosic fibers can be characterized by x-ray diffraction measurements as being amorphous or crystalline in nature. In order for cellulose to be crystalline and give an x-ray diffraction pattern, the anhydroglucose units must be oriented in a regular and repeated fashion. Various methods of measurement have shown that native cellulose has a degree of crystallinity of 50% to 94% whereas viscose rayon has 25% to 79% [33, 48].

There is no clear cut dividing line between the amorphous and crystalline portions of the cellulosic fiber. Rather, there is a variation from a high order to a low order of crystallinity. The amorphous regions of cellulosic fibers are believed to be more easily swollen and more reactive and accessible to reagents.

In addition to the chemical cross linking possible between cellulose chains as described earlier, there are other physical forces including hydrogen bonding and van der Waal's forces. All three of these forces can help hold the cellulose chains together in an oriented crystalline state.

Microorganisms that Deteriorate Cellulose

The organisms that decompose cellulose can be divided into the three following main classes: (*1*) fungi, (*2*) bacteria, and (*3*) actinomycetes. All three classes of organisms may be separated into the cellulolytic or cellulose decomposing organisms and

the noncellulolytic or surface growing organisms. Since fungi and bacteria are the most important deteriorating organisms of cellulose, only these two will be considered.

Mechanism of Deterioration of Cellulosic Fabrics

The mechanism by which the cellulolytic fungi deteriorate cellulosic fibers is not clearly understood. Siu believes that the secondary wall of the cellulosic fiber may be directly penetrated by the fungal hyphae (threadlike elements of the fungus) [39]. There is evidence for this mechanism as shown by Figure 3, in which the fungal hyphae of a cellulolytic fungi have penetrated the cotton fiber and are growing profusely in the lumen of the fiber [41]. Bright [4] has reported observing many fibers which were penetrated by hyphae from end to end within their canal without breakdown of the outer surface. Siu has explained that the fungi can penetrate to the center of the fiber through "(*1*) broken ends of hairs and deep cracks, (*2*) abrasions and shallow cracks, and (*3*) normal fiber surfaces" [41].

It is doubtful, however, that the fungal hyphae generally penetrate from the outer surface directly through the fiber wall to the center of the fiber. The pores of the fiber are too small to permit the passage of most fungal hyphae which average 5 microns in diameter. Hunt, Blaine, and Rowen [26] have shown by gaseous absorption measurements that the average pore diameter of water soaked cotton fibers is 16 Å. and that of alkali swollen cotton is 20 Å. units. Valko has shown by permeability measurements that the pore diameter in cellophane averages from 40 to 60 Å. units in diameter [34]. Of course, chance cracks and broken ends of fibers could allow some passage of fungal hyphae directly through the fiber wall into the lumen as postulated by Siu.

Greathouse [19] believes that the fungi attack the surface of the fiber and that the fungal decomposition proceeds from the outside inward. Figure 4 is a photomicrograph showing the hyphal growth around a cotton fiber [31].* This type of growth on the surface of the fiber by cellulolytic fungi is common.

With bacterial decomposition of cellulosic fibers, the degradation proceeds from the outside in, layer by layer [28]. Figure 5 [41] pictures a cotton fiber degraded by bacteria showing how the fiber has been eroded by the action of the bacteria on its surface.

It is generally believed that microorganisms cannot directly digest cellulose because it is insoluble. It is assumed that the cellulolytic types of microorganisms secrete enzymes which act as catalysts for

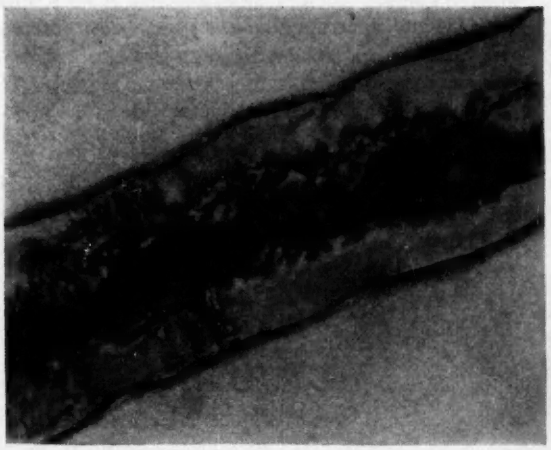

FIG. 3. *Fungal hyphae penetrating wall of cotton fiber.*

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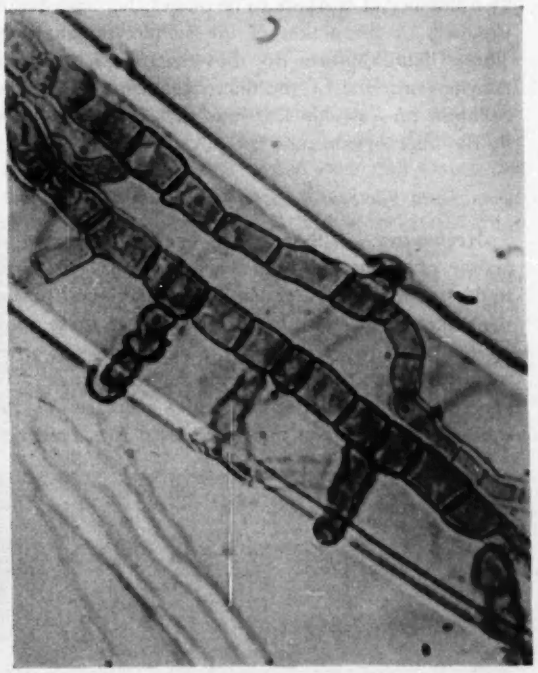

FIG. 4. *Fungal hyphae growing around cotton fiber.*

the breakdown of cellulose into soluble fractions, which are capable of diffusion into the cells of the microorganism. These enzymes released by the microorganisms are considered to be capable of permitting reactions to occur under normally unfavorable conditions.

Whitaker apparently is the first to isolate a cellulolytic enzyme. He isolated an enzyme from an enzyme preparation of *Myrothecium verrucaria* and found it to be a protein with a molecular weight of approximately 63,000, a length of 200 Å. and a width of 30 Å. [49]. This enzyme is, therefore, too large to penetrate the pores of the cotton fiber.

Impure cellulolytic enzyme preparations are effective in degrading ground filter paper [37], regenerated cellulose [29, 30], and native cellulose [3]. Blum and Stahl have found that a cell free enzyme preparation from *Myrothecium verrucaria* reduced the strength of cotton 34% in 3 to 5 days at 40°C [3]. They showed from microscopic examination that this enzyme preparation had degraded the surface of the fiber badly during this exposure. They stated that the effect of the enzyme preparation was similar to that of the cellulolytic fungi that they studied. Glucose has been found by a number of workers to be one of the degradation products of the action of the cellulolytic enzymes. These data conform to the general picture that enzymes secreted by the microorganisms decompose cellulose into soluble fractions that can be digested by the microorganisms.

Fungi and Bacteria Resistant Compounds

Mechanism.—Although the exact mechanism of action of fungicides and bactericides is not well understood, they are generally considered to poison the microorganisms. It is believed that these compounds must be very slightly water soluble in order to diffuse into the cells of the microorganism. In general, the toxicity of fungicides increases as the solubility of the agent increases; there are, however, a number of exceptions to this generalization. For applications to cellulosic fabrics, where durability to weathering is required, any appreciable water solubility is undesirable because of the loss of the agent caused by water leaching.

There are many theories of the mechanism of action of fungicides and bactericides. One of the earliest theories (proposed by Ehrlich in 1908) still sounds convincing even in the light of present day knowledge [12]. He suggested that the agents combined with chemically active groups of susceptible cells called "receptors." This chemical reaction disrupts the normal metabolic functions and brings about the death of the microorganism. There is evidence that the ability of a fungicide or bactericide to be effective is related to its ability to adsorb on the surface of the cellulosic fabric [2, 36, 46]. This property may be affected by its electrical charge [11, 32, 44]. Another property that may have a bearing on the efficiency of an agent is its ability to chelate or sequester [27]. A chelating agent may kill microorganisms by robbing them of essential metals or it may form with metals complexes that are in themselves toxic inhibitors. There is also evidence that the permeability of the agent or its ability to diffuse through a membrane is important [8, 45]. Another theory that has been advanced is that the toxic inhibitors for the cellulolytic microorganisms react with the enzymes secreted by the microorganism, interfering with their ability to break down cellulose. Regardless of the mechanism of the action of fungicides and bactericides, it is clear that these agents interrupt the usual metabolism of microorganisms and inhibit their growth.

Fungicides and Bactericides

Fungicides and bactericides may be divided into the following general classes: (*1*) Phenolic; (*2*) Metallic organic, (*a*) Copper, (*b*) Mercury; (*3*) Inorganic; (*4*) Miscellaneous.

FIG. 5. *Cotton fiber degraded by bacteria.*

Phenolics

The phenolic compounds include the chlorinated phenols and their sodium salts. Most of the chlorinated phenols are only slightly soluble in water and consequently are more widely used in applications to fabrics where durability to weathering is desired than the sodium salts which are water soluble. Of the chlorinated phenols, pentachlorophenol is one of the better fungicides. Another of the better and most widely used phenolic fungicides is 2,2′ dihydroxy, 5,5′ dichlorodiphenylmethane or G-4. Another important phenolic is salicylanilide.

Metallic organic

Of the metallic organic agents, the most important subclasses are the copper and mercury compounds. They, however, also include the zinc salts, zinc naphthenate and zinc dimethyldithiocarbamate.

Copper.—Probably the most effective, commercially available fungicide for treating fabrics exposed to outdoor weathering is copper-8-quinolinolate. This agent, in general, provides the best resistance to microbiological attack of any of the toxic inhibitors. It is available commercially in a solvent dispersible form or as an aqueous dispersion. Another effective copper compound that is widely used is copper naphthenate.

Mercury.—The phenyl and pyridyl mercuric derivatives are the most widely used organo-mercury compounds to prevent the microbiological decomposition of cellulosic fabrics. Of the commercially available phenyl mercuric agents, phenyl mercuric naphthenate is probably the most effective [1]. Of the pyridyl mercuric agents, pyridyl mercuric acetate, chloride, and stearate are probably the most efficient [1].

Inorganic

There are a great number of inorganic compounds that are claimed to be toxic inhibitors for the microbiological deterioration of cellulosic fabrics. However, only a few have had any great commercial usage. These include cuprammonium hydroxide, carbonate, and fluoride.

Miscellaneous

Of the great number of additional agents described in the literature, mercaptobenzothiazole and the quaternary ammonium compound, trimethyloctadecylammonium pentachlorophenate, are two of the more important.

Chemical Reactions with Cellulose

Cellulosic fabrics have been made resistant to degradation by cellulolytic microorganisms by chemical modifications. These modifications include acetylation, cyanoethylation, phosphorylation, and reaction with formaldehyde. All of these treatments prevent the growth of the cellulolytic microorganisms but not the noncellulolytic. In other words, they protect the cellulosic fabrics from deterioration but are not in themselves fungicidal or bactericidal.

Acetylation

Probably the earliest chemical reaction with cellulosic fabrics to protect them against cellulolytic microorganisms was acetylation. Doreé [10] in 1920 first showed that cellulose triacetate was resistant to microbiological decay. In recent years an extensive investigation of the acetylation of cotton fabrics has been made by the Southern Regional Research Laboratory of the U. S. Dept. of Agriculture at New Orleans, La. The acetylation has been carried out in pilot plant equipment at this laboratory by using mixtures of glacial acetic acid, acetic anhydride, and perchloric acid. The equipment needed for treating cotton fabric with these chemicals has to be especially constructed and is expensive. The cost of the equipment required plus that of the chemicals makes the acetylation of cotton fabrics expensive.

Acetylated cotton fabric is highly resistant to deterioration by microorganisms. For example, sandbags made of acetylated cotton have withstood two years of exposure at New Orleans [16]. Acetylated cotton with a 30% acetyl content or a degree of acetylation of 1.4 per anhydroglucose unit has withstood soil burial exposure in Panama with little or

TABLE III. ACETYLATION *vs.* RESISTANCE TO SOIL BURIAL

Acetylation (%)	Acetyl per anhydroglucose	% of strength retention (weeks) 10	30	50
0	0.0	0	0	0
19	0.9	42	22	0
25	1.2	85	67	48
30	1.4	104	100	91

no loss in strength as shown in Table III [39]. Acetylated cotton also has the advantageous property of increased resistance to high temperature deterioration [7]. A disadvantage of acetylated cotton is its relative ease of saponification.

The formula for the acetylated cellulose molecule with a degree of substitution of one is given in Figure 6.

Cyanoethylation

Another chemical modification of cellulosic fabrics that has received considerable attention in recent years is cyanoethylation. Stallings [43] showed that acrylonitrile monomer can react with cellulose as follows:

$$\underset{\text{Cellulose}}{\text{Cell–OH}} + \underset{\text{Acrylonitrile}}{CH_2 = CHCN} \rightarrow \underset{\text{Cyanoethyl cellulose}}{\text{Cell–OCH}_2\text{–CH}_2\text{–CN}}$$

This reaction is carried out by treating the cellulosic fabric with sodium hydroxide followed by acrylonitrile monomer. Because of the toxicity of the acrylonitrile monomer and its explosive properties when mixed with air, this reaction has to be carried out in a closed system. Cotton fabric treated with acrylonitrile like acetylated cotton has excellent resistance to the cellulolytic microorganisms but will not prevent the growth of the noncellulolytic. The Institute of Textile Technology at Charlottesville, Va. has made an extensive study of the cyanoethylation of cotton fabrics. Cyanoethylated cotton has other advantageous properties such as increased heat resistance. Cyanoethylated cloth with 1.5 cyanoethyl groups per anhydroglucose unit has withstood 14 days' exposure to a *Chaetomium globosum* pure culture test and 6 weeks' soil burial with no loss in tensile strength [40]. Siu has studied the effect of the degree of cyanoethylation on the resistance of the treated fabric to *Myrothecium verrucaria* as shown in Table IV [40].

These data led Siu to the conclusion that the blocking of only one hydroxyl group per anhydroglucose unit brings about resistance to microbiological deterioration.

TABLE IV. EFFECT OF DEGREE OF CYANOETHYLATION ON RESISTANCE OF FABRIC TO MICROBIOLOGICAL DETERIORATION

% N	No. of substituents per anhydroglucose unit	% Wt. loss in 13 days
0	0	80
6.6	1.0	29
8.4	1.4	6
10.0	1.9	2
10.5	2.0	4
11.4	2.4	0
12.9	2.9	0

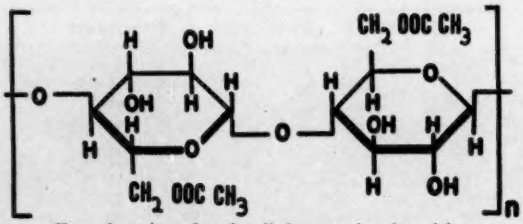

FIG. 6. *Acetylated cellulose molecule with a degree of substitution of 1.*

Phosphorylation

Another chemical modification of cellulosic fabrics that has imparted resistance to microbial deterioration is a reaction at elevated temperatures with mixtures of urea or other nitrogen containing compounds and phosphoric acid or phosphates [6]. This chemical modification of cellulosic fabrics was carried out primarily for the purpose of flameproofing but it also made the fabrics resistant to microbiological deterioration. The fabrics are treated with an aqueous solution of the phosphoric acid or phosphate and urea or other nitrogen containing compounds by padding through squeeze rolls followed by drying and then curing at temperatures of 150° to 200°C. The author believes from unpublished work carried out

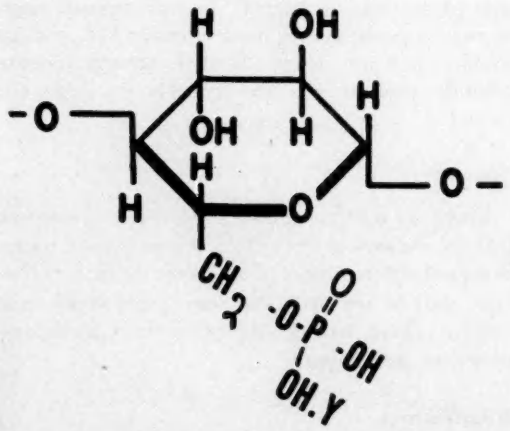

FIG. 7. *Showing the formation of a phosphate ester of cellulose. Y is a nitrogen containing basic ion and may be* NH_4.

in his own laboratory that under these conditions a phosphate ester of cellulose is formed as shown in Figure 7. *Y* is a nitrogen containing basic ion and may be NH_3.

With the above reaction, good flame and mildew resistance are obtained with a phosphorus content of approximately 3%. This phosphorus content corresponds approximately to one ester group for every 4 anhydroglucose units.

Reactions with Formaldehyde

Another chemical modification of cellulose that has produced resistance to microbial degradation is treatment with formaldehyde. Goldthwait *et al.* [17] have shown that cotton fabric treated with an acidic, aqueous solution of formaldehyde and then heated at elevated temperatures to obtain an add-on of 1.5% lost only 10% to 15% of its strength during exposure to 5 weeks of soil burial. Goldthwait proposed that the formaldehyde forms a methylene bridge across adjacent cellulose chains as

$$2\,\text{Cell–OH} + \text{HCHO} \rightarrow \text{Cell–O–CH}_2\text{–O–Cell.}$$

Wagner and Pacsu have added evidence [47] that such a methylene bridge is formed when formaldehyde reacts with cellulosic fibers under highly acid conditions. The concentration (1.5%) of formaldehyde that Goldthwait found resistant to deterioration corresponds to one methylene group to every three anhydroglucose units. One important disadvantage of formaldehyde treatment of cellulosic fabrics is the large loss in the tensile strength of the fabric during treatment. Chemical reaction of cellulose with formaldehyde as will be shown later can be considered analagous to that of melamine and urea-formaldehyde resins.

Water Soluble Aminoplast Textile Resins

Resin impregnated cotton fabrics have been shown by White and Siu [50] to be highly resistant to microbiological deterioration. Their results appeared sufficiently interesting to warrant a further investigation into the resistance of resin-treated cellulosic fabrics to microbial attack. Accordingly, cotton fabrics were treated with various water soluble, aminoplast textile resins and their resistance to both cellulolytic and noncellulolytic microorganisms was studied. It was found that none of the resins imparted resistance to noncellulolytic fungi. All of the resins studied, however, gave resistance to cellulolytic microorganisms. This resistance increased with the amount of resin used. At concentrations of 15% to 20% of resin, treated cotton fabrics showed little or no loss in strength upon exposure in a potent, soil burial bed for 6 weeks. The same fabric treated with 1% by weight of an aqueous dispersion of copper-8-quinolinolate simultaneously exposed for 6 weeks in the same soil burial bed completely disintegrated.

Textile resins of the urea and melamine-formaldehyde type in the form of aqueous solutions are used to impregnate hundreds of millions of yards of cellulosic fabrics per year. Usually the fabrics are treated by immersion in an aqueous solution of the resin and an acid forming catalyst, followed by passage through squeeze rolls, drying, and then curing at temperatures of 150° to 200°C. With the application of from 1% to 30% of these resins or combinations of these resins and water repellents, flame resistant compounds, thermoplastic resin emulsions, etc., highly desirable properties are imparted to the fabrics. Urea- and melamine-formaldehyde resins are used to impart one or more of the following properties to cellulosic fabrics: shrinkage control, wrinkle recovery, reduced moisture absorption, improved dye washfastness, slippage control, and hand. The above properties are durable and will withstand repeated washings and dry cleanings. These resins are also applied to cellulosic fabrics to produce durable mechanical finishes such as glazed and embossed fabrics. Since the aminoplast textile resins also impart to cellulosic fabrics resistance to microbiological deterioration, the property can also be added to the list of desirable effects produced by these resins. This property should be especially important for fabrics used by the Armed Services where exposure to tropical conditions accelerate micobiological deterioration.

Varying concentrations of melamine and urea-formaldehyde resins were applied to an 80 × 80 cotton fabric with an acid forming catalyst, dried at 107°C and then cured 1½ min. at 177°C. Both resins were essentially monomeric in form. They were applied at 5%, 10%, 15%, 20%, and 25% solids based on the weight of the fabric. The treated fabric samples were exposed to 2 and 6 weeks of soil burial in a leaf mold enriched, rich, garden soil containing 70% of its moisture retaining capacity in a cabinet at a temperature of 30°C with a saturated humidity. For control purposes, untreated fabric

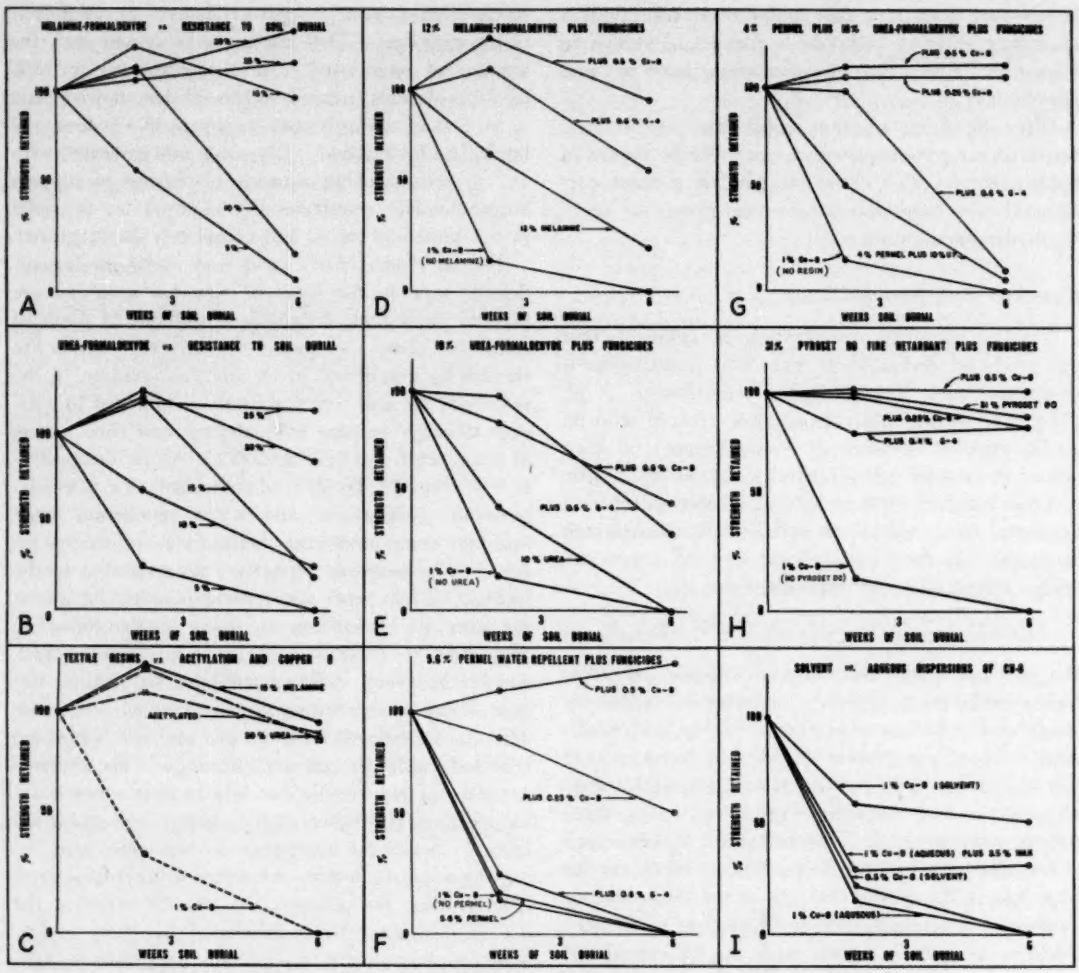

FIG. 8. *Effect of treatment with various aminoplast type textile resins and fungicides in the prevention of microbiological deterioration of fabrics.*

and fabric treated with 1% solids of an aqueous dispersion of copper-8-quinolinolate were included in the tests. Also tested was a sample of a 15.8% acetylated 48 × 48 cotton fabric, included through the courtesy of the Southern Regional Agricultural Research Laboratory.

Figure 8A is a plot of the percent strength retention of the melamine-formaldehyde treated fabrics after exposure to 2 and 6 weeks of soil burial. As can be seen, fabrics treated with 20% and 25% melamine-formaldehyde solids on the weight of the fabric show no loss in tensile strength but a slight gain even after 6 weeks of soil burial. Fabric treated with 15% of melamine-formaldehyde solids retained essentially all of its tensile strength. This concentration of resin corresponds to approximately 1 mol of resin monomer to 10 anhydroglucose units. Figure 8B gives a similar plot for urea-formaldehyde. The urea-formaldehyde treated fabric with 25% of resin solids on the weight of the fabric showed no loss but a slight gain in tensile strength after 6 weeks of soil burial. Fabric treated with 20% solids retained most of its tensile strength. This concentration of resin corresponds to 1 mol of resin monomer to 3 anhydroglucose units.

Figure 8C compares the retention of strength after

soil burial of 15% melamine-formaldehyde solids, 20% urea-formaldehyde solids, 15.8% acetylated cotton, and 1% copper-8-quinolinolate solids. As can be seen, the resin-treated fabrics are as resistant to microbiological deterioration as the acetylated fabric and much more resistant than the copper-8-quinolinolate treated fabric. It is interesting to note that at present day prices, the resin-treated fabrics are cheaper than the acetylated (estimated cost from Southern Regional Laboratory) and cheaper or equal to the copper-8-quinolinolate treated fabric.

Since the melamine- and urea-formaldehyde resins did not prevent the growth of noncellulolytic types of fungi on the treated fabric, a study was made of the effect of adding small amounts of fungicides to the resin finishes. The two fungicides chosen for this work were copper-8-quinolinolate and dihydroxydichlorodiphenylmethane or G-4. These two fungicides were chosen as described earlier in this paper because they are two of the best and also two of the most widely used. In all cases, the amount of fungicide used was half and in some cases one fourth of the normally recommended concentration for protection of cellulosic fabrics. The amount of resin applied to the fabric in each case was in the range of concentration normally used for the properties desired with the resin treatment. The resins were applied to 6-oz. diagonal weave cotton fabric with an acid forming catalyst, dried at 107°C and then cured for 1½ min. at 177°C.

Figure 8D gives a plot of the percent strength retained *vs.* time of soil burial for 12% melamine-formaldehyde solids alone and with 0.5% copper-8 and 0.6% G-4 respectively, based on the weight of the fabric. Also included in the plot as a standard for comparison is the same fabric treated with 1% copper-8-quinolinolate plus 3% of the binder recommended for use with copper-8 to improve its durability. As can be seen, 12% melamine-formaldehyde resin plus 0.5% copper-8 gave essentially no loss in tensile strength through 6 weeks of soil burial. In addition, there was no growth of fungi during a 2 week, pure culture test with *Aspergillus niger*. It is interesting to note that the combination of 12% melamine-formaldehyde and 0.5% of copper-8 gave greatly improved resistance to soil burial over that obtained by the 12% melamine-formaldehyde alone or 1% of copper-8 alone. There appears to be a synergistic effect from the combination of the two products. The loss in the tensile strength of the 1% copper-8 treated fabric during 2 weeks of soil burial is an indication of the potency of the soil burial bed. The application of 12% melamine-formaldehyde resin and 0.5% G-4 also gave good resistance to soil burial; however, it was not as effective as the combination of melamine-formaldehyde resin and copper-8.

Figure 8E is a plot of similar data for a 10% solids application of urea-formaldehyde resin. In this case also, the combination of 10% urea-formaldehyde plus 0.5% copper-8 gave the treated fabric much better resistance to microbiological deterioration than the 10% urea-formaldehyde alone or the 1% copper-8 treatment alone. The fabric treated with the combination also showed no growth of *Aspergillus niger* during a 2 week, pure culture test. A comparison of Figures 8D and 8E shows that the melamine-formaldehyde resin plus the copper-8-quinolinolate gave better protection to the fabric than the urea-formaldehyde plus copper-8. The application of 10% urea-formaldehyde resin and 0.6% G-4 also gave good resistance to soil burial.

Figure 8F is a similar plot of data obtained with 5.6% Permel Water Repellent (melamine resin base, durable water repellent) solids. Here again, as with the urea- and melamine-formaldehyde resins, the resistance to deterioration of the Permel Resin and copper-8 combination was the best. In fact, after 6 weeks' soil burial, the strength of the fabric treated with 5.6% Permel Resin solids plus 0.5% copper-8 was somewhat greater than it was initially, indicating no deterioration at all. It is probable that the increase in tensile strength was brought about by a small amount of shrinkage during the soil burial test. In this case, also, there seemed to be a synergistic effect between the Permel Resin and copper-8. It is interesting to note that the combination of Permel Resin plus only 0.25% of copper-8 gave fairly good resistance to soil burial. The Permel Resin gave considerably more resistance to deterioration in combination with copper-8 than with G-4.

Figure 8G is a similar plot to that of Figure 8F with a combination of 4% Permel Resin solids plus 10% urea-formaldehyde resin solids in place of Permel Resin. In this combination treatment of Permel plus urea-formaldehyde resin, only 0.25% or one fourth of the normally used amount of copper-8 gave no loss in tensile strength during 6 weeks of soil burial. In fact, with the combination

treatment containing 0.5% copper-8, there is an increase in tensile strength during the 6 weeks of exposure. With the combination treatments containing both 0.25% and 0.5% copper-8, there was no growth of fungi during a 2-wk. pure culture test with *Aspergillus niger*. The combination of G-4 with Permel Resin and urea-formaldehyde resin gave fair resistance to deterioration during soil burial but considerably inferior to that obtained with copper-8.

Figure 8H gives a similar comparison with an application of 31% Pyroset DO Fire Retardant solids. Pyroset DO is a nitrogenous, phosphate base, resin forming, durable fire retardant. As can be seen from the data, there is little loss in tensile strength during 6-wks. soil burial with either the Pyroset DO application alone or with the copper-8 and G-4 combinations. With a high solids of this fire retardant on the fabric, no fungicide is needed in order to prevent deterioration of the fabric during soil burial. With the Pyroset DO plus 0.5% copper-8 combination, there was no growth of *Aspergillus niger* during a 2-wk. pure culture test.

A comparison was made of solvent and aqueous dispersion applications of copper-8-quinolinolate to determine their relative efficiencies. With the aqueous dispersion, 3 parts of binder to 1 part of copper-8 were used to increase the durability of the copper-8. An application was also made of a combination of the aqueous dispersion of copper-8 plus 3.5% solids of a metallic salt, wax, water repellent plus the 3% solids binder for the copper-8. The data obtained with soil burial tests of these treated fabrics are given in Figure 8I. As can be seen, the solvent form of copper-8 was more effective than the aqueous form. Also, the addition of wax to the aqueous form of copper-8 improved the resistance of the fabric to deterioration during soil burial.

TABLE V. SOIL BURIAL RESISTANCE OF RESIN FINISHES CONTAINING 0.5% COPPER-8

Finish	Property (after wash)	Initial	After 2 weeks	After 6 weeks
Melamine	Wrinkle recovery	203°	186°	166°
Urea	Wrinkle recovery	223°	185°	173°
Permel	Spray rating	80	70	80
Permel plus urea	Spray rating	80	70	80
Pyroset DO	Char length	3.0″	4.1″	4.5″

TABLE VI. RESISTANCE OF RESIN FINISHES TO *Aspergillus niger*

Finish	Property (after wash)	Initial	After 2 weeks
Permel	Spray rating	100	100
Permel plus urea	Spray rating	100	90
Pyroset DO	Char length	3.4″	3.8″

Table V shows the retention of properties imparted to the 80 square cotton fabric by the combination resin finishes and 0.5% copper-8 after soil burial. In all cases these properties were measured after the fabric had been washed. As can be seen, the 12% melamine-formaldehyde solids and 10% urea-formaldehyde solids resin-treated fabrics retained much of their wrinkle recovery (figures given are sum of warp plus filling values) even after 6 weeks of soil burial followed by a sanforized wash. The 5.6% Permel Resin solids and the 4% Permel Resin solids plus 10% urea-formaldehyde solids treated fabrics retained their initial spray rating after 6 weeks of soil burial followed by 3 rayon washes. The 31% Pyroset DO solids treated fabric remained fire resistant even after 6 weeks of soil burial followed by 3 rayon washes. These data, in addition to those given in previous graphs, show that these resin finishes retained, to a great extent, the properties imparted to the fabric even after 6-wks. soil burial followed by washing.

Table VI shows the resistance to deterioration of the water repellent and fire retardant finishes described previously to a 2-wk. pure culture test of the noncellulolytic fungus, *Aspergillus niger*, even though this organism grew profusely on the surface of the fabric. As can be noted, the spray rating of the 5.6% Permel Resin solids application is 100 initially and after 2-wks. exposure to *Aspergillus niger* followed by 3 rayon washes. The 4% Permel Resin solids plus 10% urea-formaledhyde solids had an initial spray rating of 100 and a 90 spray rating after 2-wks. exposure to *Aspergillus niger* followed by 3 rayon washes. The Pyroset DO application which had a char length of 3.4 in. initially was 3.8 in. after 2 weeks of exposure to *Aspergillus niger* followed by 3 rayon washes. Thus, it can be seen that even though *Aspergillus niger* grew extensively on all of these resin-finished fabrics, they retained the properties imparted to them by the resin finish.

Proposed Mechanism of Resistance of Textile Resin-Finished Fabrics to Degradation by Microorganisms

White and Siu [50] assumed that the resin acted as an "inert, physical barrier preventing the fungi

and bacteria from coming into intimate contact with the cellulose." The inert barrier theory, however, is difficult to believe, since most of the resins studied were monomeric when applied and therefore diffused into the fiber.

Rather than the inert barrier theory, it is suggested that the resins chemically react with the cellulose and modify the cellulose molecule so that it is no longer food for the microorganisms. In other words, the resins chemically modify the cellulose in much the same way as acetylation, cyanoethylation, or reaction with formaldehyde to a product that is resistant to microbiological degradation. The theory that the formaldehyde containing aminoplast resins react with cellulose is not new. Cameron and Morton have proposed that these resins react with cellulose [5].

Figure 9 [9] shows a scale model of monomeric melamine-formaldehyde resin in the form of trimethylolmelamine. As can be seen, in its extended form this molecule is 12.7 Å. in length. The urea-formaldehyde monomeric molecule is, of course, smaller than the monomeric melamine-formaldehyde molecule. Since the pore size of the cotton fiber is 16 to 20 Å, and 40 to 60 Å, for regenerated cellulose, this melamine-formaldehyde molecule in monomeric form is small enough to diffuse into the inside of cellulosic fibers. Dye staining techniques have shown that this resin diffuses inside the cotton or rayon fiber. In the dye staining method, the whole fiber is dyed and then cross-sectioned. The deposition of the dye is then observed microscopically on the cross sections. With this technique, an acid dye (Calcocid Alizarine Blue SAPG) which normally does not dye a cellulosic fiber will dye the inside of a urea- or melamine-formaldehyde treated cellulosic fiber. Since this acid dye will not dye polymerized melamine- or urea-formaldehyde resin, there must be an interaction between the resin and the cellulose to make it dyeable. Moreover, a direct dye, which normally dyes a cellulosic fiber will not dye the inside of one treated with melamine- or urea-formaldehyde. In addition to these dye staining techniques which show that melamine-formaldehyde and urea-formaldehyde resins go inside the cellulosic fiber, other properties, such as high wrinkle recovery, are produced by these resins only if the resin molecule is small enough in size to diffuse into the fiber. Also resins which diffuse into the cellulosic fiber have little effect on the hand of treated fabrics compared to that of resins which are located on the surface of the fiber.

An acid colloid prepared from the melamine-formaldehyde monomer is too large to go inside the cellulosic fiber. The acid colloid is prepared by adding an acid to an aqueous solution of melamine-formaldehyde monomer. The melamine-formaldehyde then polymerizes on ageing several hours to a stabilized state of partial polymerization. Dixon, Christopher, and Salley [9] have shown by viscosity and diffusion measurements that in this form the molecule has a diameter of 60–100 Å. Since the pore size of the cotton fiber is 16–20 Å., this molecule is too large to go inside the fiber. Applications of the acid colloid to cotton fabrics do not give wrinkle resistance as with the applications of melamine-formaldehyde monomer. In addition, dye staining techniques show that no resin goes inside the cotton fiber with applications of the acid colloid.

If the theory of White and Siu [50] that the resins form an inert physical barrier between the fungi and bacteria and the cellulose were true, the acid colloid of melamine resin should impart to the cotton fabric high resistance to microbiological deterioration, since it deposits only on the outside of the fiber. To test this concept, an application was made of a 9% acid colloid of melamine-formaldehyde resin solids to 80 × 80 cotton fabric. This fabric was then exposed to a 2-wk. soil burial test. At the end of this period, the fabric had completely deteriorated. An application was also made to the same 80 × 80 cotton fabric of 8.5% solids of a highly polymerized vinyl acetate emulsion. This

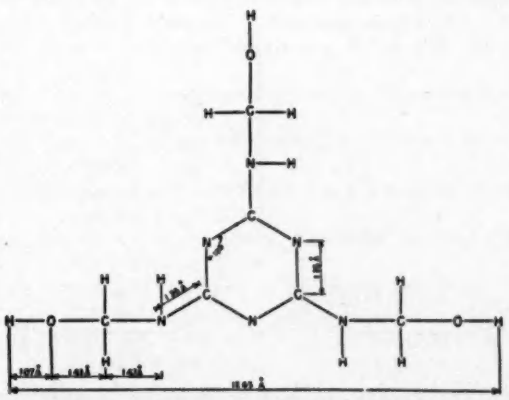

FIG. 9. *Scale model of trimethylolmelamine.*

fabric was exposed to the same soil burial test and within 2 weeks it had also completely deteriorated. If resistance to microbiological deterioration could be accomplished by coating the fibers with a thin layer of resistant material, this resin which has a molecular weight of 20,000 to 40,000 and was completely deposited on the surface of the fiber, should also prevent microbiological deterioration. These results indicate that the mechanism of the prevention of microbiological deterioration by melamine-formaldehyde resins is not by means of an inert, physical barrier.

It is suggested that the role of the urea- and melamine-formaldehyde resins in preventing the microbiological deterioration of cellulosic fabrics is to chemically react with the cellulose. It is possible that this reaction occurs between the cellulose and the melamine- or urea-formaldehyde monomer by the formation of an ether. Dimethylol urea may form a diether and trimethylolmelamine a triether with adjacent cellulose molecules. In this way cross linking between cellulose chains may occur as shown in Figure 10.

As the earlier data showed, a reaction of 1 mol of urea-formaldehyde to every 3 anhydroglucose units provides excellent resistance to microbiological deterioration. If dimethylol urea reacts with two cellulose chains, then the ratio of mols of urea-formaldehyde to reacted anhydroglucose units is approximately 1 to 1.5. With melamine-formaldehyde it was shown that only 1 mol of melamine-formaldehyde to 10 anhydroglucose units was necessary. If trimethylolmelamine reacts with three anhydroglucose units, then the ratio of mols of melamine-formaldehyde to reacted anhydroglucose units is approximately 1 to 3. An analogy can be drawn between the resin treatment of cellulose and known chemical reactions such as acetylation, cyanoethylation, phosphorylation, and formaldehyde reaction. As will be recalled, acetylation imparts to cotton fabric excellent resistance to deterioration when one acetyl group reacts with each anhydroglucose unit. With cyanoethylation, the data also indicate that one molecule of acrylonitrile is required to react with one anhydroglucose unit to impart resistance to microbiological deterioration. With phosphorylation, the resistance to deterioration is provided with approximately one phosphate group per 4 anhydroglucose units. With formaldehyde, one methylene group for every 3 anhydroglucose units is required. It should be pointed out that if the reactions with the cotton preferentially occurs in the amorphous regions of the fiber, the ratio of reactant to anhydroglucose is higher in these regions than the average value given. It is interesting to note that with chemical modifications of cellulose, it is not necessary to react at least one hydroxyl group of each anhydroglucose unit as earlier believed by some. The chemically reacted cotton fibers are also analogous to other cellulose derivatives such as cellulose acetate which are known to be resistant to microbiological deterioration. In fact, the analogy can be carried further to include nylon, acrylic, and polyester fibers which are also known to be resistant to microbiological deterioration. It would be expected that if a sufficient number of hydrophobic groups were chemically combined with the hydrophylic, hydroxyl groups of the cellulose molecule, resistance to microbiological deterioration would be thereby obtained.

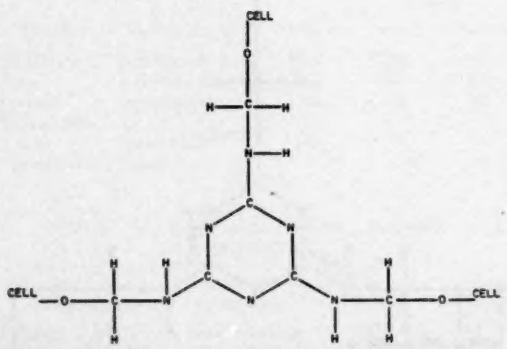

FIG. 10. *Possible reaction of melamine-formaldehyde resin with cellulose.*

To summarize, it has been shown that the thermosetting, aminoplast textile resins will provide excellent resistance to the cellulolytic microorganisms. Melamine- and urea-formaldehyde resin-treated cotton fabrics have withstood exposure to 6 weeks in a very potent, soil burial bed with no loss in tensile strength. The resin treatments have the advantages over the normally used toxic inhibitors of being completely resistant to leaching and nondermatitic to human beings. Durable water repellent and fire resistant treatments can be incorporated with these resins to provide these properties in addition to resistance to microbiological deterioration. If control of the growth of noncellulolytic organisms is also desired, fungicides and bactericides may be added but smaller amounts than normally used are required.

Acknowledgment

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Abrasion Damage of Textile Fibers*

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Abstract

The inherent abrasion behavior of 14 different textile materials in the form of yarns was investigated. Abrasion was expressed by the abrasion damage, which is the opposite of abrasion resistance. Abrasion damage was measured quantitatively by the fiber fineness (grex) destroyed in flexing around a steel bar under standardized conditions using the Stoll-Quartermaster abrasion tester. The abrasion damages were evaluated relative to that of high-tenacity nylon multifilaments. Great differences exist in the abrasion behavior of various textile fibers. The damage of multifilaments increases from nylon to Dacron polyester fiber, viscose, Fortisan, Orlon acrylic fiber, Saran, silk, acetate, and casein, while that of staple yarns increases from nylon to Dacron polyester fiber, cotton, Fibravyl, Dynel, Kuralon, Thermovyl, wool, Orlon acrylic fiber, viscose, and acetate. Staple yarns were always more abraded than corresponding multifilaments. Although high elastic energy of fibers is the main factor preventing inherent abrasion damage, extensibility, yarn surface, and friction must also be taken into account in interpreting the abrasion behavior of various textile fibers.

Introduction

When textiles in contact with solid bodies are moved relative to each other, rubbing-off or abrasion occurs. The abrading substance can be another textile or materials such as metals, glass, leather, plastics, dirt, and grit. The abrasion is a result of deformations due to compression, tension, bending, shear, and also of cutting. These and other factors cause the gradual damage of textiles in service. It is known that abrasion is a major contributing factor to wear. Kaswell emphasized recently that a clear distinction should be made between abrasion and wear [6].

For any critical judgment of the potentialities of textile materials, quantitative data on their abrasion behavior is as necessary as data on their tenacity, extensibility, elastic recovery, etc. The majority of abrasion tests of textiles have been carried out on fabrics, and they reflect only in part the abrasive behavior of the fiber material itself, since the attrition is markedly influenced here by the fabric weave, texture, and finish. Although the abrasion of yarns is also affected by form factors (yarn size, structure, twist), their influence can be reduced greatly if differences in the samples tested are kept within reasonable limits. Tests performed on multifilamentous yarns with low twist reflect mainly the abrasion of the material itself. In staple yarns, however, the yarn structure and surface affect the abrasive behavior. The yarns selected for testing were without special finishes and, considering multifilamentous and staple yarns as separate groups, they did not differ greatly in form factors.

Not much is known about the inherent abrasive behavior of textile fibers [6]. According to Backer [3], abrasion resistance decreases from nylon to cotton, wool, viscose, acetate, and casein. This rather qualitative estimation is based on the results of numerous authors obtained between 1932 and 1948 using different types of testers and widely varied fabric and yarn samples. Ray [9] obtained a similar ranking from flex abrasion tests performed on wet fabrics using the Stoll-Quartermaster tester. In these tests, nylon was found to have the highest abrasion resistance, followed by Dacron, Orlon, wool, and cotton, while viscose and acetate had the lowest resistance. Comparable quantitative data on the abrasion of different yarns were also published by Matthes and Keworkian [7, 8], Hamburger [4], and Hicks and Scroggie [5]. Using the Taber tester, Hicks and Scroggie performed tests on yarns as well as on plain-weave fabrics, and they found that

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the "abrasion life" diminished from nylon to polyacrylonitrile, viscose, and acetate approximately in the ratio 1,000:237:165:83.

The abrasion of textiles can be measured quantitatively by the progressively diminishing thickness, by loss of weight, strength, and energy absorption, and by the number (or time) of reciprocating actions (cycles) to cause a partial or total failure. Cycle numbers at break is a convenient and frequently used method of expressing the results of laboratory abrasion tests, but it is by no means the best method. Such cycle numbers indicate the abrasion life of a material and they can be compared for different fibers. It is known, however, that they are greatly influenced by many details in the testing procedure. They can be evaluated quantitatively only if obtained on the same tester under identical conditions using comparable samples.

The purpose of this study is to investigate quantitatively the abrasive behavior of various textile materials. The abrasion of yarns is compared first on the basis of cycle numbers at break. An attempt is then made to measure the inherent abrasive damage of textile fibers by the yarn grex destroyed. Abrasion damage is a characteristic opposite to that of abrasion resistance, and it expresses the amount of substance rubbed off during the test performed. Finally, the abrasion damage of various textile fibers in the form of multifilamentous and staple yarns is measured and discussed.

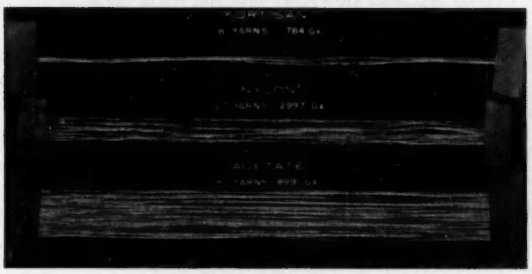

FIG. 1. *Yarn bundles.*

Yarn Abrasion

Yarn abrasion can be investigated in testers specially designed for fibers in which mostly single

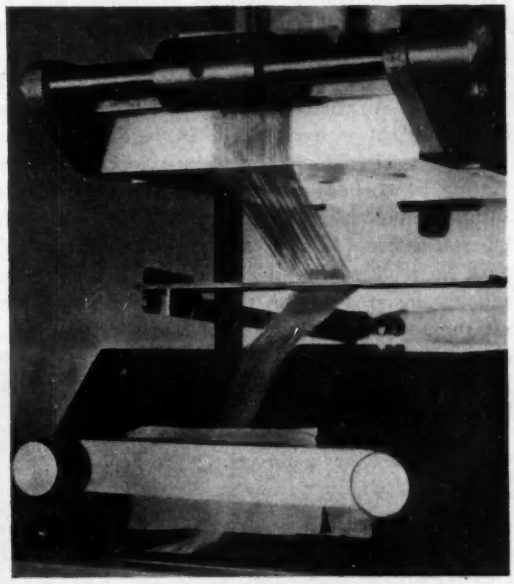

FIG. 2. *Insertion of the yarn bundle into the Stoll-Quartermaster tester.*

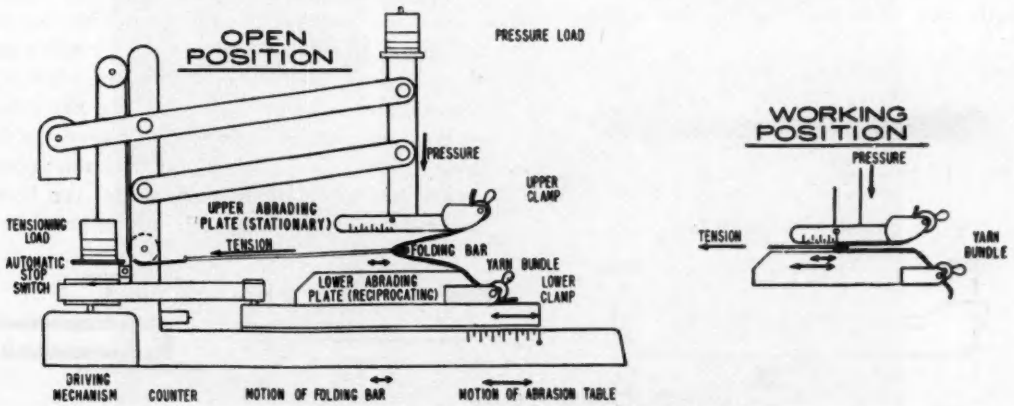

FIG. 3. *Yarn abrasion on the Stoll-Quartermaster tester.*

yarn strands are abraded. The models developed by Boehringer, Ecker, Jansen, Mecheels, Matthes (T. H. Aachen tester), Neumann, Oestermann, Weltzien, Zart [7, 8, 10, 16, 18], and Walker and Olmstead [17] represent such testers. The abrasion of yarns can be also measured quantitatively in fabric abrasion testers, in which a correlation between yarn and fabric abrasion tests is easily obtained. Such a correlation is frequently needed, either when yarns with known abrasion serve for the construction of fabrics or when abrasion tests performed on fabrics must be rechecked and interpreted by the abrasion of warp and filling yarns removed from the fabric.

The fabric abrasion testers of Schiefer, Stoll, Taber, and Wyzenbeek are the models most used in this country at present [1, 2]. In the Schiefer tester [1, 11], a circular plastic clamp is provided permitting 54 portions of the same yarn strand to be abraded simultaneously. In the Taber [5] and Stoll-Quartermaster [12, 13] testers, the fabric sample must be replaced by an assembly of parallel yarns suitably inserted in the tester. The Taber tester measures the flat abrasion of yarns against steel either parallel or perpendicular to the fiber length. Such tests were carried out by Hamburger [4] and by Hicks and Scroggie [5].

Flex Abrasion Using the Stoll-Quartermaster Tester

The tests reported in this study were performed on yarn bundles by flex abrasion using the Stoll-Quartermaster tester. The yarns were laid parallel in any desired number by a yarn reel. They were cut in sections of approximately 6 in. (15 cm.) in length, and were held together by masking tape placed on the ends, as shown in Figure 1. These two ends were clamped into the sample holders on the upper (stationary) and lower (reciprocating) abrasion plates of the tester, as shown in Figures 2 and 3. The yarn bundle itself was folded along a square-edged hardened steel bar of 2 mm. thickness (Figure 4) and inserted under tension in the tester (Figure 5). In addition, it was kept under the pressure of the abrasion head. Tension and pressure exerted on the yarns were controlled, and they were varied between 0.5 and 4.5 lbs. (227–2,041 g.) to increase or reduce the severity of the attrition. A constant stroke length of 0.5 in. (1.27 cm.), measured on the folding bar, and a constant stroke speed of 120 cycles (double strokes) per minute were maintained during all the tests performed.

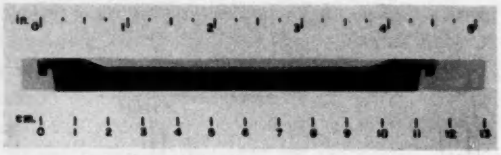

FIG. 4. *Folding bar.*

Abrasion of the yarns by rubbing and flexing took place in the tester as a result of the forward and backward motion of the folding bar. The two rather sharp edges of the bar were perpendicular to the yarn length, and they caused the main attrition of the yarn bundle. The lines of highest abrasion moved up and down along the yarn bundle length during each cycle.

Figure 6 demonstrates schematically the position of the yarn bundle and folding bar during various stages of a flex cycle. The most severe attrition occurs on that part of the bundle which is bent and pressed four times around the edges of the folding bar during a full cycle (*i.e.*, around each edge, once in the forward motion and again in the backward motion). In Figure 6 this part is cross-hatched between numbers 3 and 6 in *B* and *C*, and it is shown greatly diminished in *D*. A minor flex abrasion takes place on the neighboring parts (between numbers 2 and 3, and also between 6 and 7) which passes the edges only twice (*i.e.*, passes one edge in the forward and backward motion). The flat abrasion of the yarn bundle by rubbing (between the horizontal surface of the folding bar and the upper or lower plate of the tester, respectively) can be neglected, because it is essentially less severe than the

FIG. 5. *Position of the yarn bundle.*

abrasion by flexing around the edges of the steel bar. The yarn bundle breaks, of course, on that part where the most severe attrition takes place (Figure 6*D*).

Figure 7 demonstrates the progressive attrition of Fortisan, nylon, and acetate multifilament bundles after one-tenth, one-half, three-quarters, and all of the cycles necessary for their rupture. A permanent deformation (crimp along the folding bar) appears even at the beginning, and rupture of yarns occurs mainly at the end of the flexing procedure. After the rupture of a few yarns, the attrition proceeds very rapidly as a result of the increased tension to which the remaining yarns are subjected.* Rupture stops the reciprocating motion automatically, clearly indicating the end-point of total breakdown. All the cycle numbers reported in this study represent mean values of five tests performed under standardized atmospheric conditions, at 70°F (21.1°C) and 65% R.H. Consecutive tests were made by the same operator using the same tester and the same folding bar, and they were repeated frequently. This was considered important in view of the fact that reproducibility is a major problem in abrasion tests.

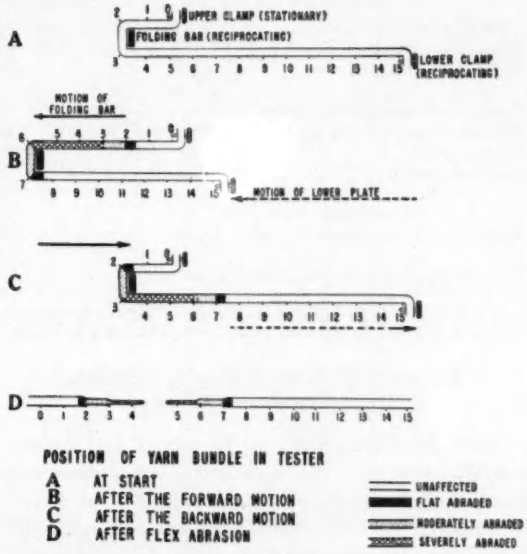

FIG. 6. *Schematic demonstration of a flex cycle.*

* This is discussed in more detail later (p. 217).

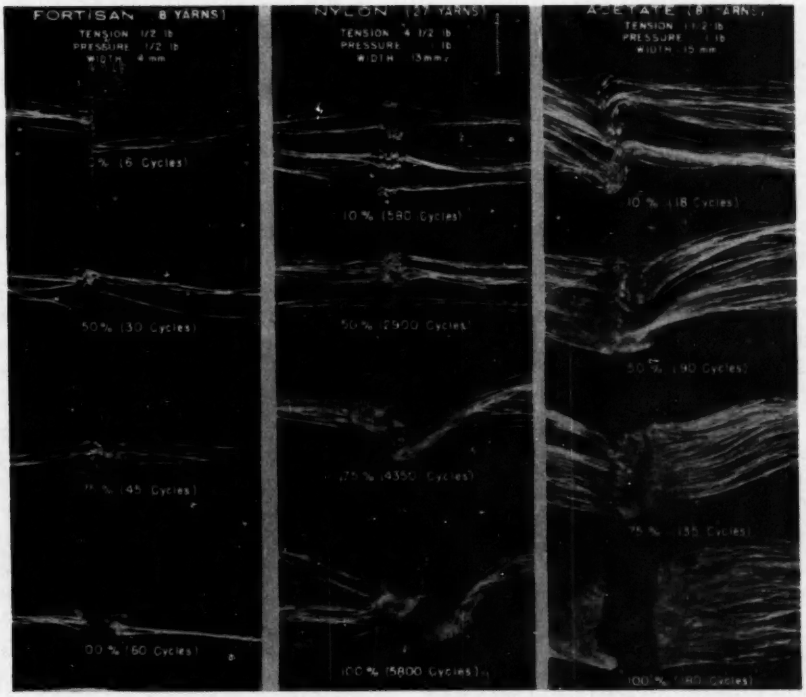

FIG. 7. *Progressive attrition of yarn bundles.*

TABLE I. FLEX ABRASION OF NYLON AND ACETATE UNDER IDENTICAL CONDITIONS *

	Nylon multifilament 100/40/2.5	Acetate multifilament 100/40/2.5	
Yarn fineness	111 gx.	111 gx.	
Tenacity at break	5.45 g./gx.	1.25 g./gx.	
Elongation at break	21.4%	24.3%	
Number of yarn strands in the bundle	27	27	108
Over-all fineness of the yarn bundle (total grex)	2,997 gx.	2,997 gx.	11,988 gx.
Actual tension	0.68 g./gx.	0.68 g./gx.	0.17 g./gx.
Relative tension	13% of ultimate	55% of ultimate	14% of ultimate
Cycle numbers at break	6,199	2	19
Relative cycle numbers	1,000	0.3	3.3
Time of abrasion in a single test	51 min. 35 sec.	1 sec.	10 sec.

* Test conditions: Stoll-Quartermaster tester; square-edged steel bar; 120 double strokes per minute; stroke length (bar), 0.5 in. (1.27 cm.); tensioning load, 4.5 lbs. (2,041 g.); pressure, 1.0 lb. (454 g.); 70°F (21.2°C); 65% R.H.

Influence of Yarn Pressure, Tension, and Bundle Size (Grex)

Yarn bundles consisting of nylon and acetate multifilaments with the same form factors were first abraded under identical testing conditions, as shown in Table I. The two fibers represent extremes with respect to abrasion behavior, since nylon multifilaments have the highest abrasion-resistance of the known textile fibers and the resistance of acetate is quite low.

Testing conditions were made identical by subjecting the acetate first to the same actual tension (0.68 g./gx.) and then to the same relative tension (13%–14%) as the nylon without changing other factors.* A high cycle number (6,199) was obtained for nylon, while the cycle numbers for acetate in both cases were very low (2 and 19). This indicates that the testing conditions were not severe enough for nylon (since an unduly long time, approximately 1 hr., was necessary for a single test), while, on the other hand, they were too severe for acetate, since rupture occurred in a few seconds. Textile fibers with such great differences in abrasive behavior must be tested under different testing conditions if the tests are to be performed in a reasonable length of time. A way must be found, of course, which permits valid comparison of cycle numbers obtained at different severities for the evaluation of different fibers.

The severity of attrition was varied by changing the pressure and tension exerted on the yarns, and also by changing the bundle size (the number of strands in the yarn bundle).

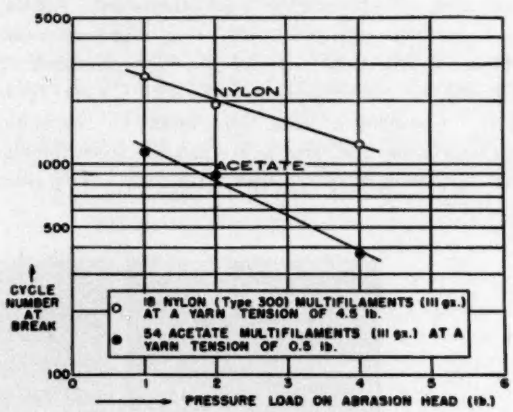

FIG. 8. *Influence of yarn pressure on cycle numbers.*

Tests at varied pressures were performed on yarn bundles of nylon and acetate multifilaments. Figure 8 shows that although a higher pressure decreases the cycle numbers at break, an increase of pressure (within the practicable limits of the tester) does not markedly influence the severity of the test. This can be accomplished better by increasing the tension. Tests at varied yarn tensions were made on yarn bundles of a spun nylon yarn and of viscose and acetate multifilaments † of different total grex (containing different numbers). An essential decrease of the cycle numbers is observable in Figure 9 at higher tensions, indicating the considerably increased severity of the abrasion. A similar decrease of cycle numbers at increasing tensions was previously ob-

* The relative tension of the acetate bundle was diminished by increasing the number of yarn strands (from 27 to 108) instead of reducing the tensioning load, which remained constant. This was necessarily connected with a much lower actual tension (0.17 g./gx.) for acetate than for nylon (0.68 g./gx.).

† The characteristics of these yarns are listed in Table IV (nos. 5, 8, and 20).

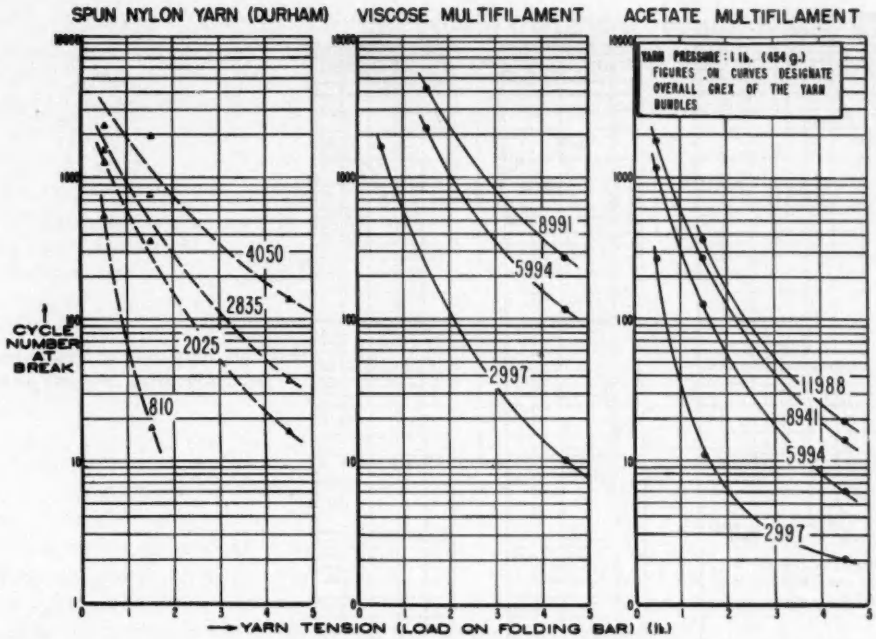

FIG. 9. *Influence of yarn tension on cycle numbers.*

served by Matthes and Keworkian [8], as shown in Figure 10. In these tests, two loops of a staple viscose yarn of varied coarseness were abraded against each other using the T. H. Aachen yarn abrasion tester. When a larger number of yarn strands or a coarser yarn is abraded, more abrasive work is required for rupture and consequently higher cycle numbers appear for all the fibers demonstrated in Figures 9 and 10.

The influence of yarn bundle size is better shown in Figure 11 and Table II. In Table II, the abrasion of nylon multifilaments and of two nylon staple yarns (60/1 Aberfoyle and 30/2 Durham) * is demonstrated in three sections representing three different severities of attrition. The severity was diminished here by reducing the tensioning load without changing the pressure. The curves of Figure 11 show that the cycle numbers increase very rapidly by increasing the yarn bundle size. The exponential relationship fully justifies the evaluation procedure suggested by Schiefer and Werntz [11]—namely, comparison of logarithms of cycle numbers instead of numerical values of cycle numbers in laboratory abrasion tests. The evaluation of these authors is more realistic than comparison of "skyrocketing" cycle numbers so far as the substance destroyed is taken into consideration. The curves shown in Figure 11 also provide the cycle numbers at break for any required bundle size, as well as the bundle size which fails in any cycle numbers within the limits of tests performed. A graphical extra-

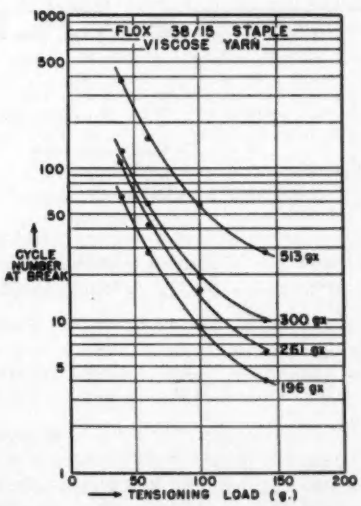

FIG. 10. *Relationship between yarn tension and cycle numbers (Matthes and Keworkian, 1943).*

* The characteristics of these yarns are listed in Table IV (nos. 1, 3, and 5).

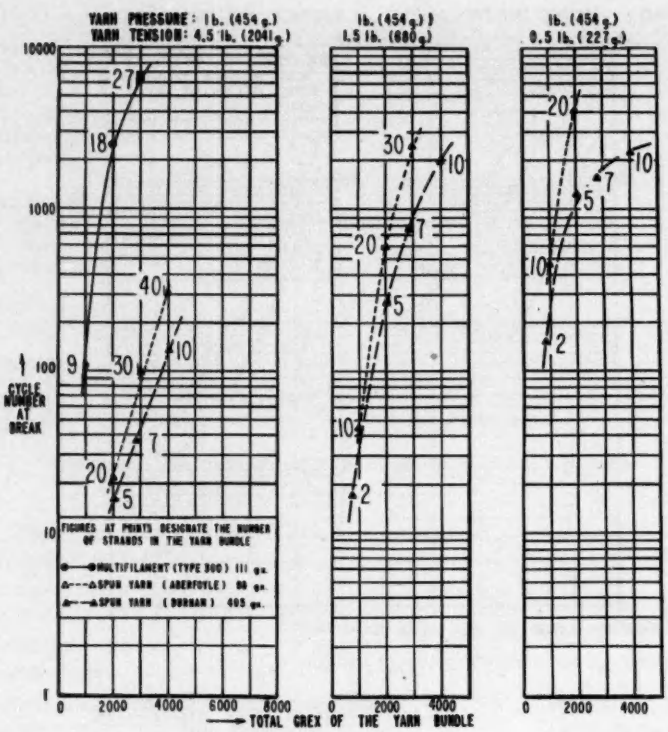
YARN PRESSURE: 1 lb. (454 g.)
YARN TENSION: 4.5 lb. (2041 g.)
1 lb. (454 g.)
1.5 lb. (680 g.)
1 lb. (454 g.)
0.5 lb. (227 g.)
CYCLE NUMBER AT BREAK
FIGURES AT POINTS DESIGNATE THE NUMBER OF STRANDS IN THE YARN BUNDLE
MULTIFILAMENT (TYPE 300) 111 gx.
SPUN YARN (ABERFOYLE) 98 gx.
SPUN YARN (DURHAM) 405 gx.
TOTAL GREX OF THE YARN BUNDLE

FIG. 11. *Influence of bundle size (grex) of nylon yarns on cycle numbers.*

TABLE II. FLEX ABRASION TESTS OF NYLON YARNS AT VARIOUS TENSIONING LOADS *

Yarn bundle		Tensioning load, 4.5 lbs. (2,041 g.) Tension			Tensioning load, 1.5 lbs. (680 g.) Tension			Tensioning load, 0.5 lbs. (227 g.) Tension		
Number of yarn strands	Total grex	Actual (g./gx.)	Relative (% of tenacity at break)	Cycle numbers at break	Actual (g./gx.)	Relative (% of tenacity at break)	Cycle numbers at break	Actual (g./gx.)	Relative (% of tenacity at break)	Cycle numbers at break
				Multifilament (Type 300) No. 1 †						
9	999	2.04	37	107						
18	1,998	1.02	19	2,500						
27	2,997	0.68	13	6,199						
				60/1 Staple Yarn (Aberfoyle) No. 3 †						
10	980				0.70	32	45	0.23	10	462
20	1,960	1.05	47	22	0.35	16	597	0.12	5	4,131
30	2,940	0.70	32	98	0.23	10	2,458			
40	3,920	0.52	24	310						
				30/2 Staple Yarn (Durham) No. 5 †						
2	810				0.84	35	17	0.28	12	154
5	2,025	1.01	42	16	0.34	14	268	0.11	5	1,238
7	2,835	0.72	30	37	0.24	10	769	0.08	3	1,540
10	4,050	0.51	21	136	0.17	7	1,979	0.06	2	2,246

* Test conditions: Yarn pressure, 1 lb. (454 g.); other conditions the same as in Table I, except when otherwise specified.
† Table IV and Figure 16.

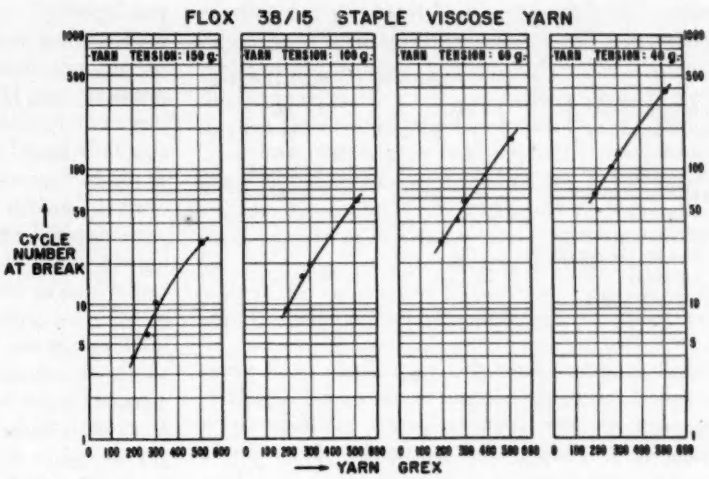

FIG. 12. *Relationship between yarn size and cycle numbers (Matthes and Keworkian, 1943).*

polation on such curves is used in a new testing technique described later (see p. 218) in order to obtain the fiber grex abraded in a constant number of cycles selected as the comparison level for the abrasion of various fibers. It can be seen from the curves of Figure 11 that an approximately linear relationship exists between the logarithms of cycle numbers and numerical values of yarn grex for points sufficiently close to each other on the curves. These observations are in full agreement with the discussed results of Matthes and Keworkian [8] obtained on different sizes (196–513 grex) of a viscose staple yarn tested at varied severities of attrition, as demonstrated in Figure 12.

Numerical data of the curves demonstrated in the three sections of Figure 11 are shown in Table II, where yarn tension appears as tensioning load (in lbs. and g.), as actual tension (in g./gx. tenacity values), and as relative tension (in % of tenacity at break). At each severity a progressively increased number of yarns was abraded corresponding to yarn bundle sizes from roughly 1,000 to 4,000 total grex.* Since the tensioning load remained unchanged in each section, the increase of the bundle size (total grex) necessarily reduced the actual and relative tensions exerted to the yarn bundle, thus also diminishing the severity of the tests. In view of this fact, the cycle numbers at break increased considerably with increasing grex of the yarn bundle.

In contrast to the tensioning load, which remains constant during the abrasion, the actual and relative tensions listed in Table II apply only to the beginning of the test. They increase with the attrition of the yarn bundle, first slowly and then rapidly until the tenacity at break is reached at the end of the test. Rupture occurs, therefore, in these abrasion tests partly as a result of an excessive tension applied to the yarns.

Comparison of Cycle Numbers

By changing the pressure and tension exerted and the number of yarn strands in the yarn bundle, it is possible to arrive at conditions under which all commercial textile fibers can be abraded using the above-described technique in a reasonable number of cycles (between 100 and 1,000) and length of time (1–8 min.) for each test.

A quantitative comparison of different fibers is possible from a series of such tests if conducted under identical testing conditions. Figure 11, for example, shows that nylon multifilaments which could be tested only at the highest severity have a much greater abrasion-resistance than the two staple yarns. The 60/1 Aberfoyle staple yarn appears slightly more resistant than the 30/2 Durham staple yarn at all three tensions. The Aberfoyle yarn is a single yarn; it is finer, has finer staple, is weaker, and is less extensible but more elastic than the Durham

* Nylon multifilament bundles could not be abraded at 1.5 lbs. and 0.5 lb. tensioning loads without increasing excessively the cycle numbers at break and the time necessary for each test.

yarn. The characteristics of these two yarns are as follows:

	30/1 Aberfoyle	60/2 Durham
Staple fineness	1.7 gx.	3.3 gx.
Staple length	1.5 in. (3.8 cm.)	1.5 in. (3.8 cm.)
Yarn fineness	98 gx.	405 gx.
Twist multiplier	3.24	3.29/2.58
Breaking tenacity	2.21 g./gx.	2.40 g./gx.
Extensibility	22.0%	31.7%
Recoverable elongation (at the breaking point)	79%	66%
Elastic energy (of total)	68%	52%

It will be shown later that high elasticity of yarns is critical for good resistance to abrasion. Conducting such abrasion tests as shown for these nylon yarns is, of course, time-consuming. Moreover, a quantitative comparison of fibers tested under different severities is not possible. Even slight changes in the testing conditions affect the cycle numbers at break considerably and in a complex way which is certainly not uniform for all textile fibers. Therefore, it is difficult to transform cycle numbers observed under different testing conditions into comparable values.

Testing Procedure Used to Obtain Abrasion Damage

A new testing and evaluation method has been used in this study in order to measure quantitatively the resistance to abrasion of various textile fibers with great differences in abrasive behavior. In these tests, the destructive action (cycle number) is kept constant, and the abrasion damage is measured. This is expressed by the grex or yarn fineness (weight per unit length) destroyed. The abrasion damage obtained for various fibers is then correlated to that suffered by nylon multifilaments, and is denoted as "relative abrasion damage." The relative abrasive damage is, therefore, a dimensionless number which indicates how much more grex of a fiber is abraded at failure than of a highly resistant nylon multifilament exposed to the same conditions. This comparison eliminates some inadequacies of the testing procedure carried out under conditions that are necessarily arbitrary.

It was found suitable to compare the abrasive damages of commercial fibers (under the above-described testing conditions) after 120 cycles, which require only 1 min. for a single abrasion test. A low cycle number was selected for comparison merely on the grounds of economy. Comparison at lower cycle numbers than 120 can hardly be recommended, but there is no objection to using higher numbers, such as 240 or even 1,200. Tests at higher cycle numbers would be appropriate for less severe abrasive actions —*e.g.*, if a folding bar with round edges, or lower pressures and tensions, or fewer cycle numbers per minute are used. Tests at higher cycle numbers would also be necessary if the rate of abrasion were to be investigated. Any change in the comparison level and in the severity of tests would, of course, affect the abrasion results obtained, and in some cases it might even affect the relative ranking of fibers with similar resistance to abrasion.

It would be difficult to find directly the fiber grex that fails in 120 cycles. This value can be obtained in a simple way, however, if yarn bundles containing varied numbers of yarns are tested which require cycle numbers close to 120 cycles for rupture. The fiber grex abraded in 120 cycles can then be obtained graphically from these tests assuming a linear relationship between the logarithms of cycle numbers and numerical values for the total grex of the yarn bundle which fails. This assumption is valid for points which lie sufficiently close to each other on the curve representing the relationship between cycle numbers and grex abraded (as shown in Figures 11 and 12), and there can be no objection to such an extrapolation if carried out within reasonable limits.

In the testing procedure, yarn bundles in two or even three different sizes were abraded for each material, at least one of them requiring less, and another more, than 120 cycles for rupture. The closer the cycle numbers approximate 120 cycles, the less is the possibility of misrepresentation due to the extrapolation and to other distorting factors. Therefore, only yarn bundles requiring more than 20 and less than 600 cycles were tested and evaluated. It is not difficult to estimate the proper number of yarn strands to be tested in the yarn bundle if the destructive action of the tester and the fineness, structure, and abrasive behavior of the yarn are known approximately. Otherwise, the suitable bundle size must be found by trial and error. This can be carried out easily in a surprisingly short time. The testing of five identical bundles to obtain an average is accomplished within a few minutes, and represents a considerable saving of time if com-

pared to conventional abrasion tests. Although the abrasion of two or even three bundle sizes increases the time necessary for performing a complete set of tests, this additional time is still moderate, and is unavoidable if reliable results are expected.

It is obvious that abrasion tests should be performed under identical conditions in order to obtain directly comparable results. Any deviations from an accepted standard procedure affect the results, and sometimes in such a way that it cannot be accounted for correctly. Unfortunately, testing conditions could not be kept identical in any respect for all commercially available yarns. They were abraded, however, under as similar conditions as feasible. Multifilaments and staple yarns with fairly similar form factors and in yarn sizes between 98 and 456 grex * were tested. The number of strands in the yarn bundle was never less than 8 or more than 80, and the over-all grex of the yarn bundle was in all but a very few cases between 1,000 and 12,000 grex. These precautions were necessary to avoid marked distortions of results.

Nylon multifilaments (which served as the basis in correlating the abrasion damages) had to be tested under a rather severe destructive action using 4 lbs. (1,814 g.) pressure and tension. Most yarns could not be abraded under the same conditions within the above limitations. Therefore, the severity of the abrasion was diminished by decreasing the yarn pressure and tension simultaneously to 2 lbs., 1 lb., and 0.5 lb. without changing other parameters. This measure made it possible to test even fibers with very low inherent abrasion-resistance within the above restrictions. Damages observed at these milder testing conditions were then transformed by calculation to make them comparable with the damage of nylon obtained at the highest severity. Viscose multifilament was selected as a reference fiber to detect quantitatively the decreased attrition brought about by the diminished pressure and tension. The medium abrasive behavior of viscose multifilament makes it convenient for testing at all four severities (4 lbs., 2 lbs., 1 lb., and 0.5 lb. pressure and tension) without deviating from the above requirements.

Details of the testing and evaluation procedure are demonstrated in Table III and Figure 13 for nylon, viscose, and acetate multifilaments of 111 gx. (nos. 1, 8, and 20, respectively, Table IV). Yarn bundles consisting of 8, 10, and 14 nylon yarn strands were abraded at 4 lbs. yarn pressure and tension. From these tests, 1,120 grex was obtained by extrapolation † as the fineness of nylon abraded in 120 cycles. (In the lower left part of Figure 13, 1,120-grex value appears at the intersection of the vertical line for 120 cycles, with the slightly inclined line representing the relationship between the grex abraded and the cycle numbers at break.) Much coarser yarn bundles of viscose (50 and 60 multifilaments) had to be tested at the same severity in order to obtain cycle numbers at break close to 120. An extrapolation gave 6,200 grex as abrasion damage of viscose in 120 cycles. The ratio between the grex values of viscose and nylon (6,200 and 1,120) is 5.53 and represents the relative abrasion damage of viscose compared to nylon. This figure indicates that 5.53 times more (by weight or grex) viscose was abraded than nylon in the abrasion tests performed.

The acetate multifilaments could not be tested under such severe conditions without greatly increasing the number of yarn strands. They were abraded under markedly milder conditions, using only 0.5 lb. pressure and tension. Acetate yarn bundles consisting of 20, 30, and 40 strands were abraded, and 2,750 grex abrasion damage was obtained in 120 cycles. Viscose was also tested as a reference fiber under these milder conditions using 8, 10, 12, and 15 yarn strands. The abrasion damage of viscose in 120 cycles was now only 1,100 grex.‡ A comparison of the abrasion damages of acetate and viscose (2,750 and 1,100 grex) shows that 2.50 times more acetate than viscose was abraded at the low severity of 0.5 lb. pressure and tension. Multiplication of this ratio (2.50) by the relative abrasion damage of viscose obtained at the high severity (5.53) gives the relative abrasion damage of acetate as 13.83 times higher than that of nylon at the high severity of 4 lbs. yarn pressure and tension. This value indicates that the same destructive action abrades acetate 13.8 times

* Although yarn size is generally expressed in denier for multifilaments and by the yarn number in cotton or worsted counts for staple yarns, the universal grex yarn numbering system was adopted to designate the yarn size. This permits the direct comparison of yarn finenesses for all the materials tested.

† In the graphic extrapolation, preference was given to cycle numbers close to 120. The cycle numbers for 10 yarn strands in Table III were obtained on different days, and they indicate the rather low reproducibility observed. Figure 13 shows, however, that the grex value of fiber damage (at the comparison level of 120 cycles) is only slightly affected by such great variations.

‡ The destruction of 1,100-grex viscose is, of course, much lower here than 6,200 grex previously according to the appreciably milder abrasive action of these tests.

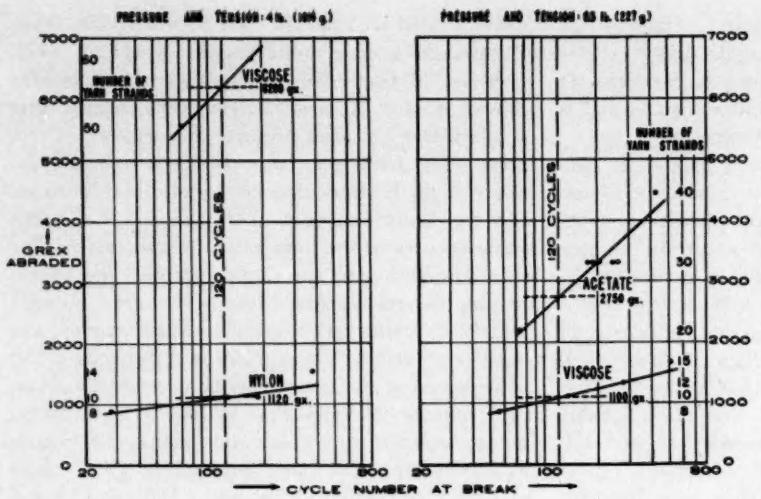

FIG. 13. *Demonstration of the testing and evaluation procedure.*

TABLE III. PROCEDURE FOR TESTING THE ABRASION DAMAGE OF NYLON, VISCOSE, AND ACETATE MULTIFILAMENTS *

Yarn bundle		Yarn tension and pressure, 4 lbs. (1,814 g.)			Yarn bundle		Yarn tension and pressure, 0.5 lb. (227 g.)		
Number of yarn strands	Total grex	Actual tension (g./gx.)	Relative tension (% of tenacity at break)	Cycle numbers at break	Number of yarn strands	Total grex	Actual tension (g./gx.)	Relative tension (% of tenacity at break)	Cycle numbers at break
				Nylon Multifilament					
8	888	2.05	38	28					
10	1,110	1.63	30	96					
10	1,110	1.63	30	123					
10	1,110	1.63	30	186					
14	1,554	1.17	21	381					
	1,120	1.63	30	120					
				Viscose Multifilament					
50	5,550	0.33	19	72	8	888	0.26	15	56
60	6,660	0.27	16	179	10	1,110	0.20	11	136
					12	1,332	0.17	10	276
					15	1,665	0.14	8	506
	6,200	0.29	17	120		1,110	0.21	12	120
				Acetate Multifilament					
					20	2,220	0.10	8	73
					20	2,220	0.10	8	75
					30	3,330	0.07	5	177
					30	3,330	0.07	5	189
					30	3,330	0.07	5	207
					30	3,330	0.07	5	245
					30	3,330	0.07	5	262
					40	4,440	0.05	4	424
						2,750	0.08	6	120

* Test conditions: the same as in Table I, except when otherwise specified.
Demonstrated in Figure 13. Characteristics of the yarns tested are listed in Table IV under nos. 1, 8, and 20.

as much as nylon. The calculated value of the relative abrasion damage of acetate is, of course, an approximation because the translation of a damage under mild conditions into one at high severity is not necessarily exactly the same for acetate as for viscose. It is known that abrasion proceeds at different rates in fibers. It can be assumed, however, that the behavior of viscose at varied severities represents with fair approximation an average progression of abrasion from which that of the other fibers tested might not deviate too significantly.

The tensions applied to the yarn bundles in the tests and at the extrapolated comparison level of 120 cycles are shown in more detail in Table III. The actual and relative tensions decrease markedly in each series of tests with increasing number of yarn strands in the bundle as an obvious consequence of increasing the bundle size (total grex) at a constant tensioning load. Besides this, the actual and relative yarn tensions at the comparison level diminish considerably from nylon to viscose to acetate according to their decreasing abrasion-resistance.* No doubt the decreased tensions affect the abrasion damages observed, since a lower yarn tension corresponds to less severe attrition. Therefore, a lower abrasion damage is obtained in these tests for fibers with low resistance than for highly resistant fibers. The tests performed favor, in a sense, fibers with low resistance and they penalize highly resistant fibers. This causes some distortion of the abrasion damages observed, which is unavoidable for tests carried out at constant pressure and tensioning loads. This distortion is not serious, however, so long as one realizes its origin and consequences. Without this distortion, the abrasion damage of poorly resistant fibers would become even higher than obtained in this study, and the "spectrum" of abrasion damage (as demonstrated in Figures 14 and 16) would appear extended in the direction of higher abrasion damage.

Abrasion tests could be performed at equal actual pressure and tension values (g./gx.), but this would require a marked change in the pressure and tensioning load for each different bundle size. They could also be performed at a fixed percentage of the breaking tenacity (*i.e.*, at identical relative tensions), but this would mean that testing fibers with different breaking tenacities and bundles of varied fineness would differ in the actual tensions (g./gx.) and in

* The significance of actual and relative yarn tensions is discussed later (see p. 225).

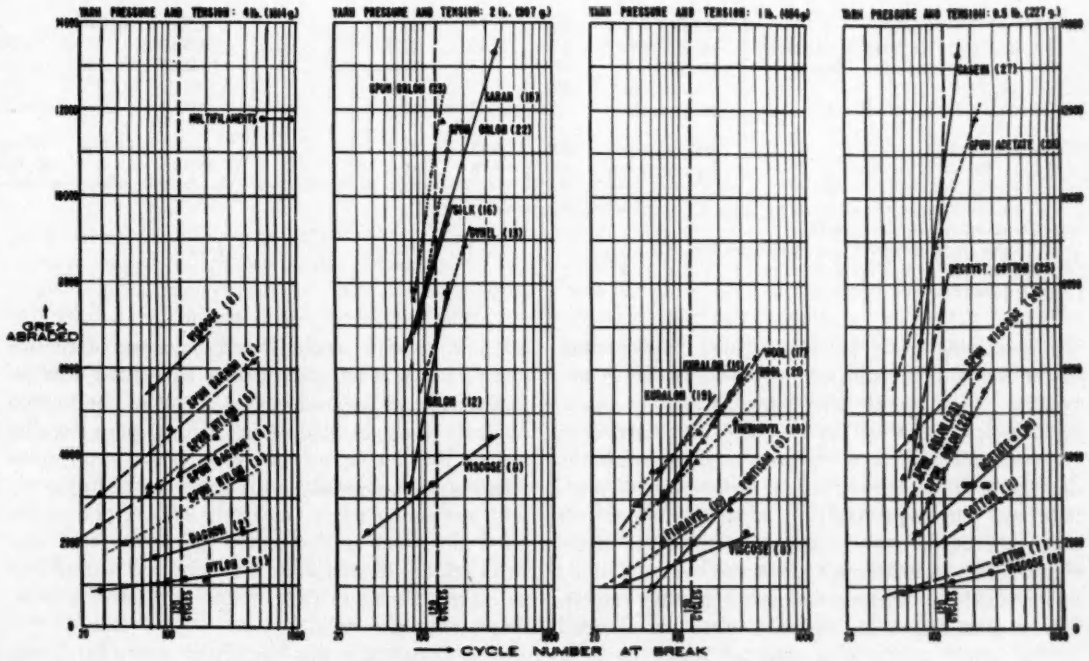

FIG. 14. *Flex abrasion tests performed on different textile materials.*

TABLE IV. ABRASION DAMAGE

1	2	3	4	5	6	7	8	9
		Characteristic			Abrasion damage observed (grex abraded in 120 cycles) Tested at a			
Designation	Yarn type	Yarn fineness (gx.)	Tenacity at break (g./gx.)	Elongation at break (%)	4 lbs. (1,814 g.)	2 lbs. (907 g.)	1 lb. (454 g.)	0.5 lb. (227 g.)
1. Nylon Type 300, 100/40/2.5	multifilament	111	5.45	21.4	1,120†			
2. Dacron polyester fiber 100/40	multifilament	111	5.28	18.1	1,800†			
3. Nylon 60/1 (Aberfoyle)	staple yarn	98	2.21	22.0	2,650†			
4. Dacron polyester fiber 20/1 (Dixie)	staple yarn	295	2.42	38.0	3,550†	1,850		
5. Nylon 30/2 (Durham)	staple yarn	405	2.40	31.7	3,750†			
6. Dacron polyester fiber 60/2 (Phaar)	staple yarn	309	2.78	39.7	4,700†			
7. Cotton 50/1	staple yarn	118	1.88	5.7		2,950		1,200†
8. Viscose 100/40	multifilament	111	1.75	15.7	6,200†	3,400†	1,700†	1,100†
9. Fortisan 90/120/3	multifilament	100	6.95	5.6			1,950†	1,150
10. Fibravyl 75/1 (Rhodia)	staple yarn	138	1.41	18.9			2,300†	1,600
11. Cotton 20/1, untreated	staple yarn	297	1.47	9.1		3,600		2,100†
12. Orlon acrylic fiber 100/40	multifilament	111	4.34	15.9	11,500	6,250†		
13. Dynel 20/1	staple yarn	296	1.10	27.5	11,750	6,650†		
14. Kuralon 40/1 (Omni)	staple yarn	146	1.44	20.0			3,900†	2,050
15. Saran 200/12/5	multifilament	222	1.88	15.3		8,600†	3,400	1,950
16. Silk 100/132	multifilament	117	4.02	21.8		8,555†	3,850	1,900
17. Wool 28.4/1	staple yarn	315	0.84	33.2			3,950†	2,480
18. Thermovyl 30/1 (Rhodia)	staple yarn	324	0.29	100.0			3,750†	2,600
19. Kuralon 80/2 (Omni)	staple yarn	144	2.44	11.2			4,600†	2,450
20. Acetate 100/40/2.5	multifilament	111	1.25	24.3			4,250	2,750†
21. Wool 45/2 (WC 3)	staple yarn	456	0.77	34.0		8,300	4,450†	
22. Orlon acrylic fiber 16/1 (Champlain)	staple yarn	369	1.86	13.7		9,300†		3,600†
23. Orlon acrylic fiber 15/1 (Newnan)	staple yarn	391	1.38	24.0		11,250†		4,400†
24. Viscose 20/1	staple yarn	296	1.26	16.2				5,250†
25. Cotton 20/1, decrystallized	staple yarn	350	1.53	17.3				7,600†
26. Acetate 20/1	staple yarn	296	0.88	21.9			13,750	9,350†
27. Casein 300/40	multifilament	333	0.78	41.0				10,500†

* Test conditions: the same as in Table I, except when otherwise specified.
† Demonstrated in Figure 14.
‡ At the (extrapolated) comparison level of 120 cycles.
** Demonstrated in Figure 16.
§ Demonstrated in Figure 17.

the tensioning loads applied. These modifications in the testing and evaluation method also distort test results. They might have some advantages under certain circumstances, but they are not superior to the procedure followed in this study, in which the damage of different materials at a standardized pressure and tensioning load is compared. No testing and evaluation process is conceivable in which viscoelastic fibers with different properties can be abraded under conditions which are identical in every respect. The various fibers, for instance, were not abraded in this study either at a constant actual or at a constant relative strain. Strain was not taken into consideration at all, although the elongation of fibers at the start of the tests (as a result of the tension applied) and also the elongation of yarn bundles during the flexing procedure influence test results. The abrasion of yarn bundles was normalized only with respect to stress (correctly with respect to the tensioning load at the beginning of the test), and this excludes simultaneous normalization with respect to other parameters (*e.g.*, actual or relative tension, strain, recovery, etc.).

It is remarkable that the actual and relative ten-

OF VARIOUS TEXTILE FIBERS *

10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Actual yarn tension‡ (g./gx.) yarn pressure and tension of:				Relative yarn tension‡ (% of ultimate)				Relative yarn abrasion damage Tested at a yarn pressure and tension of:						
4 lbs.	2 lbs.	1 lb.	0.5 lb.	4 lbs.	2 lbs.	1 lb.	0.5 lb.	4 lbs.	2 lbs.	1 lb.	0.5 lb.	Average**	Range (±%)	Ratio between multifilament and staple yarn§
1.63				30				1.00				1.0		
1.01				19				1.61				1.6		
0.68				31				2.37				2.4		1:2.4
0.51	0.49			21	20			3.17	3.02			3.1	3	1:1.9
0.48				20				3.34				3.3		1:3.3
0.39				14				4.20				4.2		1:2.6
	0.31		0.19		17		10		4.80		6.04	5.4	11	
0.29	0.27	0.27	0.21	17	15	15	12	5.53	(5.53)	(5.53)	(5.53)	5.5		
		0.23	0.20			3	3			6.36	5.78	6.1	5	
		0.20	0.14			14	10			7.46	8.06	7.8	4	
	0.25		0.11		17		8		5.84		10.54	8.0	29	
0.16	0.15			6	3			10.28	10.22			10.3	3	
0.15	0.14			14	13			10.48	10.88			10.7	2	
		0.12	0.11			8	7			12.70	10.34	11.5	10	
	0.11	0.13	0.12		6	7	6		14.00	11.06	9.86	11.6	18	
	0.11	0.12	0.12		3	3	3		13.88	12.50	9.58	12.0	18	
		0.12	0.09			14	11			12.80	12.46	12.6	1	
		0.12	0.11			41	39			12.2	13.1	12.7	4	
		0.10	0.09			4	4			15.0	12.3	13.7	9	
		0.11	0.08			9	6			13.8	13.8	13.8	0	
	0.11	0.11			14	13			13.5	14.5		14.0	4	
	0.10		0.06		5		3		15.15		18.2	16.7	9	1:1.6
	0.08		0.05		6		4		18.3		22.2	20.3	10	1:2.0
			0.04				3				26.4	26.4		1:4.8
			0.03				2				38.2	38.2		
		0.03	0.02			3	2			44.6	46.7	45.7	2	1:3.3
			0.02				3				52.6	52.6		

sion values of viscose multifilaments at the comparison level of 120 cycles remain similar in the two series of tests demonstrated in Table III and Figure 13, despite the considerable differences in the pressure and tensioning loads applied. It is obvious that if these tensions at varied severities are substantially different from each other, markedly different abrasion values can be obtained for the same yarn.

Relative Flex Abrasion Damages Observed

The new testing procedure was followed in evaluating 27 yarns (9 multifilaments, 18 staple yarns) representing 14 different textile materials with a wide range of abrasion resistance. Figure 14 and Table IV demonstrate the tests performed under four different severities using yarn pressures and tensions of 4 lbs., 2 lbs., 1 lb., and 0.5 lb. Although data are shown for clarity of presentation in Figure 14 under only one pressure for each yarn (with the exception of viscose multifilament (no. 8) and the two Orlon staple yarns (nos. 22 and 23)), most of the yarns were actually abraded under two and in some cases even three severities, as shown in Table IV. Tests with cycle numbers at break markedly different from 120 were also omitted.

The abrasion behavior of various fibers is demonstrated by more or less inclined straight lines in Figure 14. They are parts of curves showing the relationship between grex abraded and cycle numbers. The steepness of the lines indicates the rate of the attrition. The inclination increases (with

some exceptions) * in each section with increasing abrasion damage, and it shows a faster progression of attrition for less resistant yarns. The rate of abrasion is by no means identical for all fibers. Matthes [7] previously found in his yarn abrasion tests that the cycle numbers of glass fibers decreased rapidly with increasing tension, while those of other fibers decreased only moderately. This author demonstrated the abrasion behavior of five fibers (multifilaments of viscose, acetate, and glass fiber, and staple yarns of viscose and wool) by straight lines plotting the logarithm of "specific tension" † against the logarithm of cycle numbers at break (Figure 15*A*).‡ The abrasion lines have different inclinations, and they can be represented by the equation

$$s\sigma^x = \text{constant},$$

where s is the cycle number at break, σ a term for tension, and the exponent x a term for flexing. The abrasion lines connect points corresponding to tensile strength (on the ordinate) and to cycle numbers at break of samples without tension (on the abscissa). Obviously, the latter value reflects the resistance to flexing.

If the five abrasion lines close to the area of "convenient abrasion tests" (for cycle numbers between 80 and 800) of Figure 15*A* are replotted with tension values inversed, the pattern shown in Figure 15*B* is obtained. This pattern is remarkably similar to that demonstrated in the four sections of Figure 14, since a decrease in tension is equivalent in these tests to an increase in grex. The inclination of the abrasion lines increases also in Figure 15*B* with decreasing abrasion-resistance of the fibers tested. The abrasion line for glass fibers has an exceptional steepness (like those of Orlon and Fortisan multifilaments in Figure 14), and it reflects the faster progression of attrition in flexing this fiber.

In Figure 14, viscose multifilament as the reference fiber appears in all four sections. The steepness of the viscose lines decreases with diminishing severity of the tests performed, indicating again the slower progression of abrasion under less severe attrition. In the second section of Figure 14, the distance on the vertical line representing 120 cycles (between the intersection of the viscose line and the two fairly parallel lines for spun Orlon acrylic fiber) represents the range of damage which can be conveniently detected at this severity within the previously specified restrictions. This distance appears shortened in the fourth section of Figure 14, and the range of damage which can be tested at this low severity is markedly extended.

Details of these abrasion tests performed are listed in Table IV, where the fibers tested appear in order of increasing inherent abrasion damage observed,

* For example, Orlon acrylic fiber multifilaments (no. 12) in the second section and Fortisan (no. 9) in the third section.

† Specific tension (kg./mm.²) is comparable to actual tension values (g./gx.) used in this study.

‡ Figure 4 of [7].

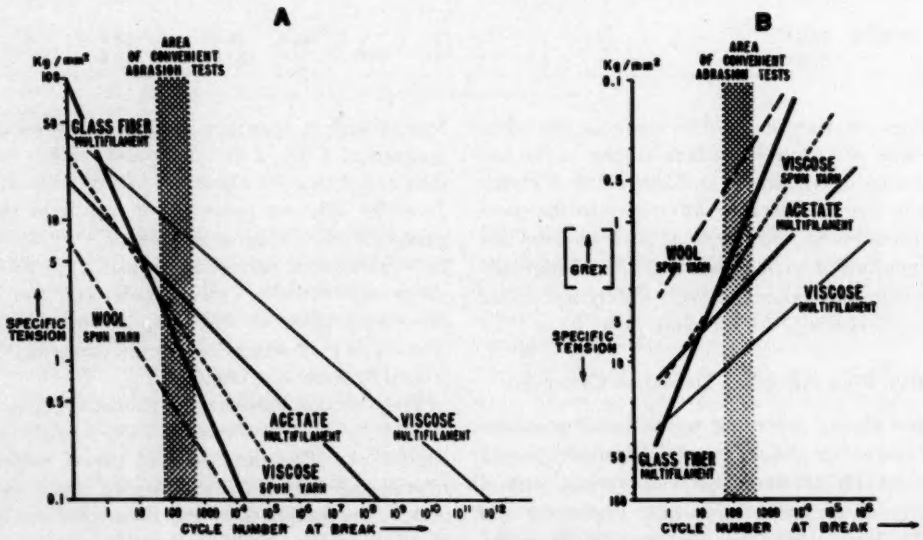

FIG. 15. *Evaluation of yarn abrasion tests performed by Matthes (1947).*

The data in columns 6–9 show clearly that the abrasion damage (the grex abraded in 120 cycles) of all fibers diminishes essentially with decreasing severity. The rate of reduction is roughly identical to that of the tensioning load. The relative abrasion damages obtained at different degrees of severity (columns 18–21), however, do not differ markedly from each other, indicating that the described evaluation method is basically correct. Deviations from the average values (columns 22 and 23) are small in most cases, the greatest being ± 29%. This is remarkable in view of the great variation of cycle numbers observed in individual abrasion tests.

Although actual and relative yarn tensions varied in the tests performed using different bundle sizes, these values are listed in columns 10–17 for that (extrapolated) bundle size which fails in 120 cycles. The data of columns 10–13 show that the actual tension (g./gx.) of the fibers tested decreased markedly with increasing relative abrasion damage of the fiber. The tests performed thus favor fibers with low abrasion-resistance. Nevertheless, the actual tension remains almost unaffected for each fiber * in tests at different severities, despite the considerable differences in the tensioning load applied. A similar, though less consistent, trend is observable when the relative tensions of the fibers tested are compared (columns 14–17).† It is noteworthy that in these tests the ratio between the highest and lowest relative tension (41% and 2%) is markedly less than that for actual tensions (1.63 and 0.02 g./gx.). It is obvious that yarn abrasion should be tested at relatively low tensions, since otherwise the response observed will be that to tension rather than that to abrasion. On the other hand, the tension should not be so low that an excessively long time is necessary for testing, especially when highly resistant fibers are abraded. The actual and relative tension values shown in Table IV were not preselected, but appeared spontaneously as a result of the four tensioning loads applied to the yarn bundles. They represent a fortunate and workable compromise between the conflicting requirements for tension limits.

The average values of relative abrasion damage (column 22, Table IV) are demonstrated graphically in Figure 16 for multifilaments and for staple yarns. A logarithmic scale was selected here to show the small differences in yarns with low abrasion damage (high abrasion resistance) and also the great differences among the textile fibers.

The quantitative data obtained permit the classification of textile fibers into three main groups. The first group (with relative abrasion damage below 5) contains multifilaments and staple yarns of nylon and Dacron polyester fiber corresponding to excellent resistance to abrasion. The majority of textile fibers belong in the second group (relative abrasion damage between 5 and 25) with medium damage. The last group (values above 25) comprises the few materials with high damage or poor resistance to abrasion, and includes staple yarns of viscose, decrystallized cotton, and acetate, and casein multifilament.

Among the new synthetic fibers, only Dacron polyester fiber is comparable to nylon. The damage of Orlon acrylic fiber by abrasion is markedly higher

* Exceptions are nos. 7, 10, and 11.

† Apparently, the values shown for nos. 2, 9, 12, and 16 are too low, while those for nos. 17, 18, and 21 seem to be too high. No explanation can be given for these deviations from the rule.

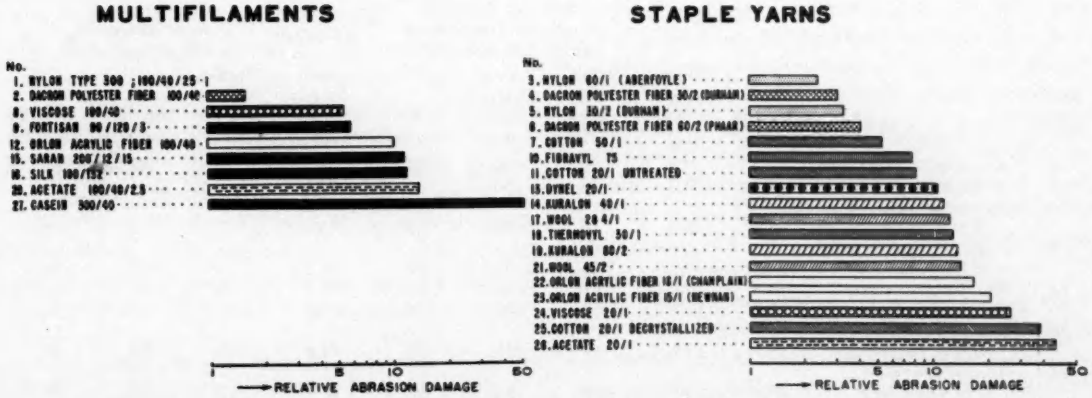

FIG. 16. *Relative abrasion damage of various textile fibers.* (Correction: *No. 4 should read "Dacron polyester fiber 20/1 (Dixie)."*)

and not very different from that of viscose. The behavior of the synthetic staple yarns Fibravyl, Dynel, and Kuralon is remarkable. These fibers are considerably more affected by abrasion than staple nylon and Dacron polyester fiber, but appreciably less than staple viscose and acetate. The abrasion damage of cotton yarns is also fairly low, except when the cellulose is present in a decrystallized form [15]. No doubt the form factors and finish of the yarns tested affect the results. Great differences in the form factors of multifilamentous and staple yarns were avoided, and no special finishes were used, so that the results would not be unduly affected thereby. Different staple yarns of the same fiber material * had different form factors and were obtained mostly from different sources, but their relative abrasion damages were very similar as compared to the large differences observed among the various textile materials.

* Staple yarns of 60/1 and 30/2 nylon, 20/1 and 60/2 Dacron polyester fiber, 50/1 and 20/1 cotton, 40/1 and 80/2 Kuralon, 28.4/1 and 45/2 wool, and 16/1 and 15/1 Orlon acrylic fiber.

No.
3 NYLON 60/1 (ABERFOYLE)
5 NYLON 30/2 (DURHAM)
4 DACRON POLYESTER FIBER 20/1 (DIXIE)
6 DACRON POLYESTER FIBER 60/2 (PHAAR)
22 ORLON ACRYLIC FIBER 16/1 (CHAMPLAIN)
23 ORLON ACRYLIC FIBER 15/1 (NEWNAN)
24 VISCOSE 20/1
26 ACETATE 20/1
1 2 3 4 5

FIG. 17. *Ratio between relative abrasion damage of multifilaments and staple yarns.*

Although the ranking of multifilaments with respect to abrasion damage is essentially the same as that of staple yarns, the relative abrasion damage of spun yarns was always found to be higher than that of multifilaments. The individual staple fibers sticking out from the yarn surface can be easily pulled out or cut through. This causes a loosening and untwisting of the yarns which increases the attrition further if tensional and bending forces act upon the yarn. The ratio between the relative abrasion damage observed for multifilaments and staple yarns (column 24, Table IV) varied from 1:1.6 (for 16/1 Orlon acrylic fiber) to 1:4.8 (for viscose), as demonstrated in Figure 17. A higher abrasion damage of staple yarns has also been observed by other authors. Matthes [7] found a lower resistance to abrasion of viscose, cuprammonium, and acetate staple yarns as compared to multifilaments using the T. H. Aachen yarn abrasion tester. Lower abrasion life was also observed by Hicks and Scroggie [5] for staple yarns than for multifilaments in flat abrasion tests of viscose yarns performed on the Taber tester.

The difference is slight between the relative abrasion damage observed for the two samples of nylon, Dacron polyester fiber, Kuralon, and Orlon acrylic fiber staple yarns, as demonstrated in Figure 16. It is also noteworthy that, with the exception of Kuralon, the less extensible and more elastic sample of each pair suffered the lower damage, despite the fact that considerably lower total energy was necessary for its rupture. In the case of nylon and Dacron

TABLE V. THE ELASTIC BEHAVIOR OF STAPLE YARNS OF NYLON, DACRON POLYESTER FIBER, ORLON ACRYLIC FIBER, AND KURALON

No. in Table IV	Designation	Relative abrasion damage*	Elongation at break (%)	Relative values of elongation components at the breaking point: Immediate elastic recovery	Delayed recovery	Unrecoverable	Total energy of rupture for 1 m. fiber length (g.-cm./gx.)	Relative values of work components (% of total work): Immediately recoverable	Creeping recoverable	Unrecoverable
3	Nylon 60/1 (Aberfoyle)	2.4	22.0	20	59	21	20.2	13	55	32
5	Nylon 30/2 (Durham)	3.3	31.7	13	53	34	35.6	6	46	48
4	Dacron polyester fiber 20/1 (Dixie)	1.6	38.0	10	22	68	46.9	7	17	76
6	Dacron polyester fiber 60/2 (Phaar)	4.2	39.7	11	20	69	57.1	8	11	81
14	Kuralon 40/1 (Omni)	11.5	20.0	11	39	50	15.5	9	33	58
19	Kuralon 80/2 (Omni)	13.7	11.2	18	54	28	12.8	12	54	34
22	Orlon acrylic fiber 16/1 (Champlain)	16.7	13.7	19	55	26	14.8	12	59	29
23	Orlon acrylic fiber 15/1 (Newnan)	20.3	24.0	16	34	50	22.9	10	31	59

* See column 22, Table IV, and Figure 16.

polyester fiber, the more resistant sample had also a slightly lower tenacity at break. The superior elasticity of the yarns with lower abrasion damage is revealed by the lower relative values of their unrecoverable elongation component at the breaking point and of their unrecoverable work component (listed in Table V).* The higher flex abrasion damage of the less extensible, markedly stronger, and more elastic 80/2 Kuralon yarn is apparently the result of some "overstretching," which makes the fiber less resistant to forces acting transverse to the fiber length (flexing, shear).

Factors Preventing Abrasion Damage

It will be worthwhile to discuss some factors which prevent abrasion damage. According to Hamburger [4, 6], good abrasion-resistance (low damage) depends more on high energy necessary for rupture than on high tenacity at break. It is obvious that abrasion will be influenced not so much by the work absorbed in the first deforming process (total energy of rupture) as by the work absorbed during repeated deformations. This work is manifested in the elastic energy or the recoverable portion of the total energy (the sum of immediately recoverable and creeping recoverable work components). It is also revealed in the work absorption of fibers after repeated deformations (mechanical conditioning). It is obvious that the energies necessary for breakdown in compression, bending, and shear are as important for the evaluation of flex abrasion as the energy necessary for rupture in tension (when deforming forces act parallel to the fiber length). Unfortunately, the former energies are unknown, but their relative ranking for textile fibers is presumably not greatly different from that in tension. Therefore, the elastic energies in tension (as revealed by the areas under the recoverable elongation of the stress-strain curves) permit at least a qualitative interpretation of abrasive damage in most cases.

Drawn nylon multifilaments require the highest energy for rupture among the known commercial textile fibers because of their high tenacity and high extensibility. The predominant part of this total energy is recoverable due to the high elasticity of drawn nylon. The tensile properties of high-tenacity nylon multifilaments remain almost unaffected by mechanical conditioning [14], and, consequently, the work absorption does not diminish markedly if the deformation is repeated. This prevents the destruction of nylon by frequently repeated flex abrasion, and is responsible for its extraordinarily low abrasion damage. On the other hand, staple nylon yarns usually have lower tenacity and elasticity but higher extensibility than multifilaments. They are, of course, markedly affected by mechanical conditioning, which diminishes their energy necessary for rupture after the first deformation. An additional disadvantageous factor here is the looser yarn structure. The abrasive damage of staple nylon yarn is, therefore, higher than that of nylon multifilaments.

Wool yarns require a relatively high work for rupture, despite their rather low tenacity. Their elastic behavior is also excellent, and is comparable to that of nylon. No appreciable loss in work absportion occurs in the repeated tensioning of wool. This explains the comparatively low abrasion damage observed for wool yarns. The properties favoring low damage by abrasion are not present to such a degree in casein. Therefore, casein suffers a much higher destruction than wool, despite the similar tenacities and extensibilities of the two fiber types.

Extensibility is also a critical factor in flex abrasion. In frequent flexing of yarns around sharp edges, a considerable elongation at the outside curvature of bent fibers takes place. If this elongation exceeds the extensibility of the fiber, rupture will invariably occur. Although brittle fibers (glass fibers) may have low flex abrasion resistance, too high an extensibility favors flex abrasion damage, especially if the unrecoverable portion of the elongation (permanent set) is considerable. In such cases (*e.g.,* in acetate, decrystallized cotton) the fiber length increases and the fiber cross section diminishes in each cycle. This, in turn, causes stress concentrations and reduced resistance to forces acting perpendicular to the fiber axis (shear), resulting in rupture. It has been shown that in the case of staple yarns of nylon, Dacron polyester fiber, and Orlon acrylic fiber, the less extensible and more elastic samples suffered lower abrasion damage.

The yarn surface, too, is no doubt an important factor for abrasion damage. Finishes may prevent easy detachment of single fibers, particularly in staple yarns, and also may harden and smoothen the yarn surface, thus reducing the friction. On the other

* The actual values of the recoverable energies are not listed in Table V. They were higher for the sample of each pair having the lower abrasion damage, except in the case of Kuralon.

hand, finishes might stiffen yarns and prevent the free mobility and yielding of single fibers in the yarn structure, thus enhancing abrasion damage. All the above factors must be considered in order to understand fully the damage of textile fibers by abrasion.

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The Stability to Water Leaching of Some Textile Fungicides Applied to Unlined Flax Forestry Fire Hose*

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Introduction

Among the fabrics which, because of the circumstances of their use, would appear to be exposed to severe conditions of microbiological attack, must be numbered the unlined flax hose used by the forestry fire-prevention services of the federal and provincial governments in Canada, as well as by many pulp and paper companies.

Large quantities of this hose are used, the annual replacement being approximately 3 million feet. Much of the hose is used under conditions which preclude the care which, under less urgent circumstances, could be given it. Thus, for example, thorough and quick drying after use is not always possible; and the hose, coming into intimate contact with the ground, is therefore subject to contamination with soil microflora, many of which are known to be cellulolytic. Moreover, the water used in forestry fire-prevention work, and obtained from streams and rivers, frequently contains an abundance of cellulolytic organisms, and hence hose, dampened with such water and allowed to remain damp for considerable periods, may be expected to suffer appreciable damage.

It is not suggested that microbiological damage is the prime cause of hose failure. There is no doubt that the obvious damage that hose suffers during use, through abrasion against rock and stones, contributes heavily to its failure, and the relative importance of these two hazards—*viz.*, microbiological attack and abrasive wear—has long been the subject of argument. It is, however, generally agreed that since the possibilities of damage by microbiological attack are so obvious, it is desirable to incorporate into the hose a suitable fungicide as resistant as possible to the conditions of use outlined above.

Given below is a summary of the main requirements covered in Specification 13-GP-1-1945, "Linen Hose, Forestry Type," of the Canadian Government Specifications Board, which governs the purchase of much of the hose used in Canada:

The hose is woven from yarns spun from first quality flax line. The amount of vegetable gum in the yarn, as determined by an empirical alkali boil, is limited to not more than 8%. The fabric is required to be uniformly even and to be free from knots and shives. The diameter of the hose is 1.57 ± 0.03 in. and its weight not more than 14 lbs./100 ft. The hose is required to withstand a static bursting pressure of 600 lbs./in.^{2} when tested with water. The leakage of the hose is limited to not more than 3.4 ml./min. at a water pressure of 100 lbs./in.^{2} and 14.2 ml. at 200 lbs./in.^{2}.

It will be noted that a certain amount of seepage of water through the hose fabric is permitted, the reason for this being to protect the outside of the hose from damage from hot embers with which the hose is frequently in contact during use. This, together with the passage of water through the interior of the hose, subjects any fungicide used to a severe leaching action and hence the ability of a given fungicide to withstand severe leaching is one of the first requirements to be met.

The work reported here was undertaken at the request of the Committee on Fire Hose of the Canadian Government Specifications Board and covers the stability to leaching of a number of textile fungicides which have been used or suggested for use in unlined flax forestry fire hose.

Experimental

Compounds Investigated.

These are given in Table I.

Preparation of Samples

The compounds were applied in the laboratory to randomized portions of a continuous 300-ft. length

* N. R. C. Publication No. 3228.

of hose meeting the requirements of the above specification. Compounds *A*, *B*, *D*, and *E* were applied from solution in Stoddart solvent. Compound *C* was diluted with water before application. Compound *F* was applied as received.

In all cases the compounds were applied from baths of appropriate concentrations to give the required add-on of compound. The concentration of the bath was based on the wet pick-up of the solvent by the fabric, allowance being made for the greater viscosity of the more concentrated solutions. Small samples of the hose were treated, analyzed, and any necessary adjustment in bath concentration made, before treating the larger samples used in the leaching experiments. 14-in. specimens of hose were cut open along one side, opened out, and immersed in the solution in a large beaker (to avoid evaporation of solvent) for 60 sec. They were then drained for 30 sec. by holding up on edge, and then put through squeeze rolls with 3 thicknesses of blotting paper on each side, using a fresh piece of paper against each specimen.

Eight 14-in. samples were prepared for each concentration of the six compounds. Each sample gave eight 6-in. × 1-in. ravelled strips for breaking strength measurements. The distribution of the samples for each concentration of the six compounds is given in Table II.

Leaching and Soil Burial Tests

The leaching periods chosen were 30 days and 60 days as well as the 24-hr. period normally carried out on all fabrics to be subjected to the standard soil burial test [2]. The treated samples were placed in jars of 2,750 cc. capacity. Only samples treated with the same compound were leached in the same jars. The leaching was carried out with tap water at a temperature of 25° ± 1.0°C, and at a rate of flow of 10 l./hr. At the end of the leaching period, the samples were removed, those for burial being given a 2-week burial test under the standard conditions specified [2], and the balance retained for the initial breaking strength tests.

TABLE I

Designation of compound	Composition
A	Copper naphthenate concentrate containing 8% copper metal. Solvent-soluble.
B	Solvent-soluble preparation of dodecyldimethylbenzylammoniumnaphthenate containing approximately 50% of active ingredient.
C	Water-dispersible preparation of dodecyldimethylbenzylammoniumnaphthenate containing approximately 50% of active ingredient.
D and *E*	Preparation of solubilized [1] copper 8-hydroxyquinolinolate, soluble in solvent, obtained from two different manufacturers, and containing 1.8% copper metal.
F	A film-forming compound comprising an aqueous dispersion of synthetic resins and containing approximately 2.5% salicylanilide.

Breaking Strength Measurements

Before determining the breaking strength of the original and buried samples, they were conditioned at a temperature of 70° ± 2°F and a relative humidity of 65% ± 2%. Breaking strength determinations were made on a 0–1000 lb. constant rate of traverse Suter horizontal tester machine operating at a pulling speed of 12 in./min. using ravelled strips, 6 in. × 1 in., with the long dimension in the warp direction, with 3 in. between the jaws. The average of 8 to 12 determinations was taken as the value for each sample. The percentage breaking strength loss was determined by comparison with the controls which had been leached only.

Determination of Fungicides in Samples

The samples were analyzed after impregnation to determine the amount of compound present initially. These analyses were repeated at the end of the 30-day and the 60-day leaching periods, respectively. The percentage loss of compound, as a result of leaching, could then be estimated. Copper in the copper naphthenate treated samples was determined by the ignition method, in the copper 8-hydroxyquinolinolate samples by the spectrographic method, and dodecyldimethylbenzylammoniumnaphthenate by a method already described [3].

Appearance of Samples Before and After Leaching and After Soil Burial

After treatment, the samples treated with compound *C* were less stiff and more pliable than the

TABLE II

Leached 24 hrs.	1 sample
Leached 24 hrs. and buried 2 weeks	1 sample
Leached 30 days	1½ samples
Leached 30 days and buried 2 weeks	1½ samples
Leached 60 days	1½ samples
Leached 60 days and buried 2 weeks	1½ samples

rather stiff untreated original fabric, but all the other treated samples were much stiffer than the untreated, even at the low concentrations. This stiffness was particularly noticeable in the case of compounds *A* and *F*. At the end of the leaching periods, the stiffness had disappeared in all cases.

The color of the copper naphthenate treated samples was a blue green, the depth of color increasing with the concentration. There was no change in color of the samples treated with compounds *B*, *C*, and *F*. The samples treated with compound *D* were greyish green, and with compound *E* a yellowish green, the depth of color depending on the concentration in each case.

At the end of the leaching periods, the copper naphthenate samples were much faded and blotchy in appearance, this effect being more pronounced at the end of the 60-day period. The samples treated with compounds *D* and *E* were all somewhat faded at the end of 30 days, and, at the end of the longer leaching period, the color faded to the color of the original fabric except in the case of the highest concentration of each compound. The appearance of the samples was quite uniform. The untreated samples showed some brownish discolored, brittle patches, this effect being much more noticeable after the 60-day period.

At the end of the burial period, the untreated sample and those treated with compounds *B*, *C*, and *F* were covered with large brown patches, and small brown, black, yellow, and orange spots. They all had a slightly moldy odor, were very slimy to the touch when wet, and on drying had a brittle feel and were obviously thinner than before burial. The sample with the lowest concentration of copper naphthenate showed finely spotted areas, white, pink, and mauve in color. The sample treated with compounds *D* and *E* showed some brown or reddish brown areas and some scattered orange spots, but did not show obvious thinning or brittleness and possessed no odor.

Discussion

Breaking Strength Losses

The data for loss in breaking strength on leaching and burial are given in Table III.

TABLE III. EFFECT OF LEACHING AND SOIL BURIAL ON FLAX HOSE TREATED WITH VARIOUS FUNGICIDES

Treatment		Breaking strength of samples (lbs.)						Breaking strength loss of leached samples after burial for 2 weeks (%)			Breaking strength loss of leached samples (%)	
		Leached 24 hrs.		Leached 30 days		Leached 60 days						
Compound	Content of active ingredient (%)	Control	Buried 2 wks.	Control	Buried 2 wks.	Control	Buried 2 wks.	Leached 24 hrs.	Leached 30 days	Leached 60 days	Leached 30 days	Leached 60 days
Untreated control		664	103	514	—	428	—	84	—	—	23	35
A	0.42 Cu	738	757	719	648	758	701	0	10	7		
	1.04 Cu	698	707	715	722	743	738	no significant loss				
	1.40 Cu	735	788	761	742	775	764	no significant loss				
B	0.55	666	170	705	103	624	140	74	85	78		
	1.25	670	508	691	359	659	193	24	48	71		
	1.70	677	636	691	315	646	335	6	54	48		
	2.00	682	622	691	540	641	322	9	22	50		
C	0.52	673	406	662	42	621	127	40	94	80	no significant loss	no significant loss
	1.00	668	524	696	175	614	133	21	75	78		
	1.46	659	590	680	468	661	222	10	31	66		
	2.07	656	685	679	601	638	366	0	11	43		
D	0.036 Cu	623	656	659	651	663	621	no significant loss				
	0.082 Cu	623	621	667	653	693	640	no significant loss				
	0.185 Cu	611	609	626	620	679	657	no significant loss				
E	0.106 Cu	673	720	675	705	696	642	no significant loss				
	0.223 Cu	673	734	689	715	701	725	no significant loss				
F	Approx. 0.4 salicyl-anilide	633	319	628	87	677	96	50	86	86		

It is interesting to note that leaching alone caused pronounced loss in breaking strength in the case of the untreated control, this amounting to 23% at the end of 30 days and to 35% at the end of 60 days. This progressive loss in strength is attributed to microbiological attack, since the time of the year at which the leaching was carried out (May, for the 30 day period, and June and July for the 60 day period) would favor the presence of cellulose destroying organisms in the tap water used. This observation is believed to be a highly significant one as it confirms the suspicion that, under conditions of use in the field, an appreciable amount of attack may result from the action of microorganisms in the water used in the hose. In the laboratory experiments the water used was the filtered Ottawa River water as supplied to the City of Ottawa, but it would nevertheless seem that it contained cellulolytic microorganisms which, over a period of time, were capable of establishing themselves on the untreated fabric and attacking it. Similar, if not more severe, results may be expected from the water from rivers and streams normally used in fighting forest fires.

The effect of a 2-week burial period, following upon each of the leaching periods, indicates that samples containing copper as copper naphthenate, at concentrations from 0.4% to 1.4% copper, showed no appreciable loss of strength, even after the longest period of leaching. This was equally true of the samples containing copper in the form of copper 8-hydroxyquinolinolate (compounds *D* and *E*) although the percentage of copper was exceedingly low (0.04% to 0.22%) compared with the percentage of copper as copper naphthenate. Compounds *B* and *C* did not show any great ability to withstand leaching. At the end of 30 days, only the highest concentration of both *B* and *C* could be said to afford moderate rot protection, and this protection was lost by the end of a 60 day period of leaching. Compound *F* showed unsatisfactory resistance to leaching, affording only slight protection to the fabric upon burial, even when the leaching period was only of 24 hrs. duration. This may be partly due to the low concentration (approximately 0.40%) of the active ingredient (salicylanilide) of the compound present initially in the treated fabric.

All of the treatments to which the hose was subjected, with the exception of compound *F* and the lowest concentration of *B* and *C*, would be considered satisfactory from the point of view of rot-resistance, as judged by the standard 2-week burial test after 24 hrs. of leaching; but after 30 or 60 days of leaching, of the various treatments investigated, only the compounds containing copper, either as copper naph-

TABLE IV. LOSS OF TREATING COMPOUND ON LEACHING

Treatment	Content of active ingredient (%)			Loss of compound (%)	
	Original	Leached 30 days	Leached 60 days	Leached 30 days	Leached 60 days
Compound *A*	0.42 Cu	0.372	0.375	12.5	11.8
	1.04 Cu	0.944	0.985	9.2	5.3
	1.40 Cu	1.29	1.215	7.8	13.2
Compound *B*	0.55	0.27	0.18	50.9	66.4
	1.25	0.60	0.48	51.6	61.2
	1.70	0.86	0.78	49.4	53.8
	2.00	1.02	0.83	50.0	59.3
Compound *C*	0.52	0.14	0.08	73.3	84.8
	1.00	0.28	0.14	74.6	88.6
	1.46	0.46	0.24	68.3	83.3
	2.07	0.57	0.38	72.3	81.4
Compound *D*	0.036 Cu	0.031	0.027	13.9	25.0
	0.082 Cu	0.077	0.066	6.1	19.5
	0.185 Cu	0.155	0.143	16.2	22.7
Compound *E*	0.106 Cu	0.084	0.085	20.8	20.0
	0.223 Cu	0.213	0.217	4.4	2.7
Compound *F*	Approx. 0.4 salicylanilide	—	—	—	—

thenate or as copper 8-hydroxyquinolinolate, showed sufficient resistance to water leaching to give complete protection to the fabric.

Loss of Treating Compound

The data for loss of treating compound on leaching are given in Table IV.

It will be seen that the loss of copper from the copper naphthenate treated samples was relatively low. Most of the loss of copper seems to take place within the first 30 days of leaching. This also applies to the copper content of the samples treated with compound *E*. The copper content of the sample treated with the copper 8-hydroxyquinolinolate compound (*D*), seems to decrease as the leaching period is extended. Approximately 50% of compound *B* was lost from the samples at the end of 30 days leaching, and this loss increased to approximately 60% at the end of 60 days. The samples treated with compound *C* showed an even greater loss, 68–75% at the end of 30 days, increasing to around 85% at the end of the 60 days leaching period.

Relation Between Content of Treating Compound and Protection Against Deterioration on Leaching Followed by Burial

In general, for each of the compounds investigated, the breaking strength loss seems directly related to the amount of proofing compound present on the sample at the time of burial. A copper content of 0.37% in the form of copper naphthenate gives practically complete protection. In the case of samples treated with the solubilized copper 8-hydroxyquinolinolate, a copper content as low as 0.027% gives complete protection.

With compounds *B* and *C* the amount of protection afforded was low, except for the highest percentages and even here the protection was much inferior to that imparted by the copper compounds. For these compounds it would appear that where, in service, the hose is required to withstand conditions as severe as those corresponding to 60 days of leaching followed by 2 weeks of soil burial, it would be necessary to have an initial content of compound of 4–6% (2–3% active ingredient).

The general relation between the contents of the various compounds, except *F*, and the loss of breaking strength on burial is shown in Table V.

Conclusions

1. Of the compounds tested, those containing copper appear to show the greatest stability to leaching and to afford the greatest protection after prolonged leaching and subsequent soil burial.

2. Any of the copper compounds tested could be readily applied to linen forestry fire hose and, it is

TABLE V. RELATION BETWEEN CONCENTRATION OF ACTIVE INGREDIENT PRESENT IN SAMPLE AFTER LEACHING AND THE PERCENTAGE LOSS OF BREAKING STRENGTH ON BURIAL

Compound	Concentration of active ingredient present in sample after leaching (%)	Loss breaking strength on burial (%)	Adequacy of protection
A	0.372, 0.375 } 0.374 Cu	no significant loss	excellent
	0.944, 0.985 } 0.965 Cu	no significant loss	excellent
	1.29, 1.21 } 1.25 Cu	no significant loss	excellent
B	0.18	78	
	0.27	85	very poor
	0.48	71	
	0.60	48	
	0.78	48	moderate
	0.83	50	to poor
	0.86	54	
	1.02	22	probably adequate
C	0.08	80	
	0.14	94	
	0.14	78	very poor
	0.24	66	
	0.28	75	
	0.38	43	moderate
	0.46	31	to poor
	0.57	11	good
D and *E*	0.027, 0.031 } 0.029 Cu	no significant loss	
	0.066 Cu	no significant loss	
	0.077 Cu	no significant loss	
	0.085 Cu	no significant loss	excellent
	0.143 Cu	no significant loss	
	0.155 Cu	no significant loss	
	0.213, 0.217 } 0.215 Cu	no significant loss	

believed, would afford satisfactory protection against microbiological attack throughout the life of the hose, if used in sufficient amount.

3. Regarding the choice of copper compound—*i.e.*, as between copper naphthenate and copper 8-hydroxyquinolinolate—it would seem that the latter is to be preferred. This conclusion is based on the surprisingly high efficacy of the latter compound when present in very small amounts. Thus, the data show that a treatment with 2% of compound *D* gives the same degree of protection as does 13% of copper naphthenate, the relative amounts of copper being 0.036% and 1.04%, respectively. Moreover, the effect of copper 8-hydroxyquinolinolate on the physical properties of the hose—*i.e.*, stiffening, increase in weight, and impairment of seepage characteristics—is known to be far less marked than in the case of copper naphthenate.

4. The fungicidal properties of the compounds containing dodecyldimethylbenzylammoniumnaphthenate and salicylanilide are not considered adequate for the protection of unlined flax forestry fire hose.

Acknowledgments

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The Exact Pattern of a Concentration-Dependent Diffusion in a Semi-infinite Medium, Part III*

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Introduction

Previous papers of this series [4, 5] dealt with the exact solutions of Fick's diffusion equation in one dimension with variable diffusion coefficients of the forms

$$D(C) = \frac{D(0)}{1 - \lambda C}, \qquad (1)$$

$$D(C) = \frac{D(0)}{(1 - \lambda C)^2}, \qquad (2)$$

where C is the concentration of diffusing substance, and λ is an arbitrary constant (positive). Although these forms of $D(C)$ are of considerable interest in that they represent D-C plots resembling rather closely the rapidly increasing diffusion coefficients, which are often observed in polymer-solvent or polymer-sweller systems, it must be mentioned that these $D(C)$ equations are not significantly different from one another in the sense that they both are functions which increase monotonously with increasing concentration. Recently, in accordance with the conclusion from a general discussion by Hartley [6] concerning the diffusion behavior in a swelling high-polymeric solid, several investigators observed another type of concentration dependence of the diffusion coefficient in which the diffusion coefficient passes through a maximum between the much lower values obtained at the extremes of the concentration diagram. Thus, Robinson *et al.* [3, 9] observed such a D-C relationship for systems consisting of cellulose acetate and

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some organic solvents, such as chloroform, acetone, methylene chloride, etc.; Long and his colleagues [7] also encountered some examples of this type for similar systems in which the polymer was polyvinyl acetate. In view of these experimental findings, it seems of considerable interest, not only theoretically but also practically, to attempt investigations of mathematical problems of diffusion which are associated with diffusion coefficient-concentration relationships of this type.

Some time ago, Crank and Henry [2], using a numerical method of solution, worked out in detail a diffusion problem of this kind. However, since they limited their considerations to the changes which occur in the shapes of absorption-time and desorption-time curves when the diffusion coefficient exhibits a maximum at an intermediate concentration in the concentration range concerned, no information was given in their paper about the concentration distribution in the material through which diffusion takes place. Later, Crank [1] attempted to calculate the concentration-distance curve in a system with $D(C)$ of this type by approximating the given D-C plot by a step-function, as illustrated in Figure 1. So far, no theoretical calculation other than these two appears to have been published in the literature as regards the diffusion equation with $D(C)$ showing a maximum point.

Recently, the present author found that the Fick diffusion equation in one dimension with a diffusion coefficient of the form

$$D(C) = \frac{D(0)}{1 + 2aC + bC^2}, \qquad (3)$$

where a and b are arbitrary constants, can also be integrated analytically with the same initial and boundary conditions as adopted in Part I or II of this series. This form of $D(C)$ in itself presents some interesting properties. First, equation (3) contains, as special cases, equations (1) and (2): by putting $a = -\lambda/2$ and $b = 0$, it reduces to equation (1); when $a = -\lambda$ and $b = \lambda^2$, it is the same as equation (2). Second, the quadratic form with two arbitrary constants, appearing in the denominator of the equation, allows a wide variety of D-C plots: (a) a monotonously increasing type; (b) a monotonously decreasing type; (c) a type in which a maximum appears; and (d) a type in which a minimum exists. It can be shown that by proper choice of a and b values, D-C plots are obtained which bear close resemblance to the above-mentioned experimental results of Robinson *et al.* and Long *et al.* The diffusion coefficient-concentration relations which exhibit a minimum at an intermediate concentration in the concentration diagram have also been noted by several investigators [8] for cases in which dissolved particles of macromolecules diffuse in their dilute solution; however, such cases are beyond the scope of the present series, which is concerned chiefly with the diffusion process of a low-molecular-weight substance in a high-polymeric solid.

It is possible to carry out the mathematical analysis of the diffusion problem relating to equation (3) without setting any limitations to the values of the arbitrary parameters a and b. However, such a general treatment of the problem was found to involve a very lengthy and cumbersome analysis, and did not necessarily appear to be of particular interest. Therefore, we shall present here only the results of analysis for the case in which $D(C)$ goes through a maximum at a concentration between the extremes of the concentration range concerned.

The Formal Solution

Retaining the nomenclature of the previous papers, the diffusion equation to be solved is written

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D(C)\frac{\partial C}{\partial x}\right], \qquad (4)$$

where $D(C)$ is given by equation (3), and the initial and boundary conditions to which the required solution is subject are as follows:

$$C = 0 \qquad (t = 0, x > 0), \qquad (5)$$

$$C = C_o \qquad (t > 0, x = 0). \qquad (6)$$

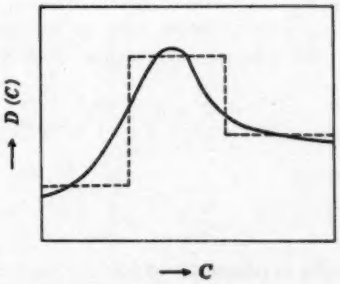

FIG. 1. *Crank's approximation of* D(C) *by a step-function.*

By introducing the dimensionless variables, defined by

$$\frac{C}{C_o} = c, \quad \frac{x}{2\sqrt{D(0)t}} = \eta, \quad aC_o = \alpha, \quad bC_o^2 = \beta, \quad (7)$$

equation (4) reduces to an ordinary differential equation of the form

$$\frac{d}{d\eta}\left(\frac{1}{1 + 2\alpha c + \beta c^2}\frac{dc}{d\eta}\right) = -2\eta\frac{dc}{d\eta}, \quad (8)$$

and conditions (5) and (6), respectively, change to

$$c \to 0 (\eta \to \infty), \quad (9)$$

$$c = 1 (\eta = 0). \quad (10)$$

As noted, we are here concerned only with a particular case of $D(C)$, in which it passes through a maximum between $C = 0$ and $C = C_o$. The condition for this must first be sought. This condition is equivalent to that in which the function $f(c)$, defined by

$$f(c) = 1 + 2\alpha c + \beta c^2, \quad (11)$$

has a minimum between $c = 0$ and $c = 1$. It can easily be shown that such a condition is satisfied by

$$0 < -\alpha/\beta < 1, \quad (12)$$

$$\alpha < 0. \quad (13)$$

Hence, β must necessarily be positive:

$$\beta > 0. \quad (14)$$

Physically, any maximum of $D(C)$ appearing in the concentration range concerned must be finite, which means that the corresponding minimum of $f(c)$ must be positive. This is fulfilled by the condition

$$1 - \alpha^2/\beta > 0. \quad (15)$$

Thus, the required conditions for the present purpose are given by the four conditions from equations (12) to (15). For convenience, writing $\alpha = -\gamma$, the conditions in question may be summarized, in terms of the positive quantities of β and γ, as follows:

$$0 < \gamma/\beta < 1, \quad (16)$$

$$0 < 1 - \gamma^2/\beta. \quad (17)$$

By putting

$$\frac{dc}{d\eta} = -\varphi, \quad (18)$$

equation (8) is transformed to

$$\frac{d}{dc}\left(\frac{\varphi}{1 - 2\gamma c + \beta c^2}\right) = 2\eta. \quad (19)$$

By differentiating both sides of this equation with respect to c, taking equation (18) into account, and putting

$$\psi = -\frac{\varphi}{1 - 2\gamma c + \beta c^2}, \quad (20)$$

equation (19) becomes

$$\frac{d^2\psi}{dc^2} = -\frac{2}{(1 - 2\gamma c + \beta c^2)\psi}, \quad (21)$$

which, on introducing the variables ϕ and z, defined by

$$\phi = \sqrt{\beta}\psi, \qquad z = \frac{\beta}{\sqrt{\beta - \gamma^2}}\left(c - \frac{\gamma}{\beta}\right), \quad (22)$$

reduces to

$$\frac{d^2\phi}{dz^2} = -\frac{2}{(1 + z^2)\phi}. \quad (23)$$

This equation can be integrated analytically, giving as the first integral:

$$(1 + z^2)\frac{dU}{dz} = \pm (\lambda - U^2 - 8 \ln U)^{\frac{1}{2}}, \quad (24)$$

where

$$U = \sqrt{2}\phi/\sqrt{1 + z^2}, \quad (25)$$

and λ is an integration constant. By simple integration of equation (24), we obtain the following two integrals:

$$\tan^{-1}z + \mu_1 = \int^U (\lambda - q^2 - 8 \ln q)^{-\frac{1}{2}}dq, \quad (26)$$

$$\tan^{-1}z + \mu_2 = -\int^U (\lambda - q^2 - 8 \ln q)^{-\frac{1}{2}}dq, \quad (27)$$

where μ_1 and μ_2, respectively, are integration constants corresponding to the plus and the minus signs in the right-hand side of equation (24).

It is realized that when the variable c moves from 0 to 1, the variable z moves from $-\gamma/(\beta - \gamma^2)^{\frac{1}{2}}$ to $[\beta/(\beta - \gamma^2)^{\frac{1}{2}}] \times [1 - (\gamma/\beta)]$, where, since $\beta > 0$, $\gamma > 0$, $0 < \gamma/\beta < 1$, and $0 < \beta - \gamma^2$, according to the conditions given above, the quantities k and m, defined by

$$k = \frac{\gamma}{\sqrt{\beta - \gamma^2}}, \quad m = \frac{\beta}{\sqrt{\beta - \gamma^2}}\left(1 - \frac{\gamma}{\beta}\right), \quad (28)$$

are both positive. The relation between c and z is shown graphically in Figure 2.

The boundary condition (9), combined with equations (18), (19), (20), (22), and (25), results in

the following conditions

$$U \to 0 \quad (z \to -k), \tag{29}$$

$$\frac{dU}{dz} \to \infty \quad (z \to -k). \tag{30}$$

Also, from the second boundary condition (10), combined with equations (19), (20), and (22), we have

$$\frac{d\phi}{dz} = 0 \text{ at } z = m. \tag{31}$$

From equation (25), it follows that

$$(1 + z^2)\frac{dU}{dz} = \sqrt{2(1 + z^2)}\frac{d\phi}{dz} - zU, \tag{32}$$

which, on substitution of the condition (31), gives

$$(1 + m^2)\left(\frac{dU}{dz}\right)_{z=m} = -m(U)_{z=m}. \tag{33}$$

It can generally be established, for any diffusion process which obeys the Fick equation (4) subject to the subsidiary conditions (5) and (6), that if $D(C)$ is positive for any C belonging to the concentration range concerned, C is a decreasing function of the distance diffused. Taking this general relation into account, it can easily be shown that for the diffusion system herein considered the quantity U must be positive for any value of z in the range $-k < z \leqq m$. (It should be noted that U approaches zero as $z \to -k$, according to condition (29).) By applying this result to equation (33), we obtain

$$\left(\frac{dU}{dz}\right)_{z=m} < 0. \tag{34}$$

The conditions (30) and (34) indicate that dU/dz is opposite in sign at the two ends of the concentration range being considered. By combining this result with the differential equation (24), it is realized that when z moves from $-k$ to m, the corresponding $U(z)$ must change from the positive solution of equation (24)—*i.e.*, equation (26)—to the negative solution—*i.e.*, equation (27). Designating by z_* the value of z at the point where the two solutions coincide, the following relation from equation (24) is valid:

$$\lambda - U^2 - 8 \ln U = 0 \quad \text{at } z = z_*. \tag{35}$$

The solutions (26) and (27) may then be specified as follows:

$$\tan^{-1}z + \mu_1 = \int^U (\lambda - q^2 - 8 \ln q)^{-\frac{1}{2}}dq \quad (-k < z < z_*), \tag{36}$$

$$\tan^{-1}z + \mu_2 = -\int^U (\lambda - q^2 - 8 \ln q)^{-\frac{1}{2}}dq \quad (z_* < z < m). \tag{37}$$

Denoting by U_* the value of U determined by equation (35), and putting

$$\frac{U}{U_*} = \theta, \quad \frac{8}{U_*^2} = \epsilon, \tag{38}$$

equations (36) and (37) may be written

$$\tan^{-1}z + \mu_1 = \int^\theta (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq \quad (-k < z < z_*), \tag{39}$$

$$\tan^{-1}z + \mu_2 = -\int^\theta (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq \quad (z_* < z < m). \tag{40}$$

Substitution of the condition (29), which is expressed in terms of θ as $\theta \to 0 (z \to -k)$, into equation (39) determines the unknown constant μ_1, resulting in

$$\tan^{-1}z + \tan^{-1}k = \int_0^\theta (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq \quad (-k < z < z_*). \tag{41}$$

Since it is obvious that $\theta = 1$ at $z = z_*$, we have

$$\tan^{-1}z_* + \tan^{-1}k = \int_0^1 (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq. \tag{42}$$

The condition (33) can be expressed in terms of θ as

$$(1 + m^2)\left(\frac{d\theta}{dz}\right)_{z=m} = -m(\theta)_{z=m}, \tag{43}$$

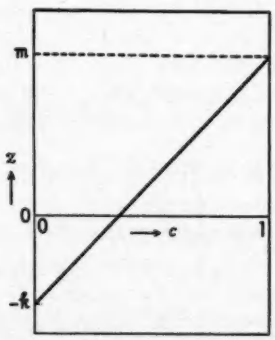

FIG. 2. *Relation between z and c according to equation (22).*

substitution of which into equation (40) leads to

$$\epsilon \ln \theta_m + (1 + m^2)\theta_m^2 = 1, \qquad (44)$$

where θ_m stands for the value of θ at $z = m$. By applying the obvious condition that $\theta = \theta_m$ at $z = m$ to equation (40), the unknown constant μ_2 is eliminated, giving

$$\tan^{-1}m - \tan^{-1}z = \int_{\theta_m}^{\theta} (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq \qquad (z_* < z < m). \qquad (45)$$

Since $z = z_*$ at $\theta = 1$, this equation gives

$$\tan^{-1}m - \tan^{-1}z_* = \int_{\theta_m}^{1} (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq. \qquad (46)$$

Eliminating z_* from equations (42) and (46) results in

$$\tan^{-1}k + \tan^{-1}m = \int_0^1 (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq + \int_{\theta_m}^1 (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq. \qquad (47)$$

Combination of this equation with equation (44) allows for the determination of the unknown parameters ϵ and θ_m as functions of the parameters k and m. Both k and m are evaluated from their definition equations (28) in terms of β and γ, which are the essential parameters of the present problem. Both equations (44) and (47) are transcendental, and are so complicated in form that the evaluation of ϵ and θ_m for given values of β and γ must be made numerically by the use of a trial-and-error method. It is seen from equation (44) that when ϵ is positive, as in the present case, θ_m is smaller than unity. It is then convenient to rewrite equation (47) as

$$\tan^{-1}k + \tan^{-1}m = 2\int_0^1 (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq - \int_0^{\theta_m} (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq. \qquad (48)$$

On introducing a new function, $F(\theta; \epsilon)$, where

$$F(\theta; \epsilon) = \int_0^{\theta} (1 - q^2 - \epsilon \ln q)^{-\frac{1}{2}}dq, \qquad (49)$$

the above equation may be abbreviated as follows:

$$\tan^{-1}k + \tan^{-1}m = 2F(1; \epsilon) - F(\theta_m; \epsilon). \qquad (50)$$

Similarly, in terms of $F(\theta; \epsilon)$ thus introduced, equations (41) and (45), respectively, may be put in the forms:

$$\tan^{-1}z = F(\theta; \epsilon) - \tan^{-1}k \quad (-k < z < z_*), \qquad (51)$$

$$\tan^{-1}z = \tan^{-1}m - F(\theta; \epsilon) + F(\theta_m; \epsilon) \qquad (z_* < z < m). \qquad (52)$$

The equation from which the value of z_* may be evaluated is obtained from equation (42) or from equation (46), resulting in

$$\tan^{-1}z_* = F(1; \epsilon) - \tan^{-1}k. \qquad (53)$$

Returning back to the original variable, c (dimensionless concentration), as determined from z of equation (22), equations (51), (52), and (53), respectively, result in the following equations:

$$c = \frac{\sqrt{\beta - \gamma^2}}{\beta} \tan [F(\theta; \epsilon) - \tan^{-1}k] + \frac{\gamma}{\beta} \qquad (0 < c < c_*), \qquad (54)$$

$$c = \frac{\sqrt{\beta - \gamma^2}}{\beta} \tan [\tan^{-1}m - F(\theta; \epsilon) + F(\theta_m; \epsilon)] + \frac{\gamma}{\beta} \quad (c_* < c < 1), \qquad (55)$$

$$c_* = \frac{\sqrt{\beta - \gamma^2}}{\beta} \tan [F(1; \epsilon) - \tan^{-1}k] + \frac{\gamma}{\beta}. \qquad (56)$$

In evaluating these equations as functions of θ, it should be noted that while in equation (54) the parameter θ can move from 0 to 1, in equation (55) the parameter θ is limited to the narrower range from θ_m to 1. The former limitation can be ascertained from equation (41), while the latter limitation of θ can be understood from equation (45).

By combining equation (19) with equations (20), (22), and (32), we obtain

$$\eta = \frac{1}{2\sqrt{2}} \sqrt{\frac{\beta}{\beta - \gamma^2}} \times \left(\sqrt{1 + z^2} \frac{dU}{dz} + \frac{z}{\sqrt{1 + z^2}} U \right). \qquad (57)$$

Substitution from equation (24) gives

$$\eta = \frac{1}{2\sqrt{2(1 + z^2)}} \sqrt{\frac{\beta}{\beta - \gamma^2}} [zU + (\lambda - U^2 - 8 \ln U)^{\frac{1}{2}}] \quad (-k < z < z_*), \qquad (58)$$

$$\eta = \frac{1}{2\sqrt{2(1 + z^2)}} \sqrt{\frac{\beta}{\beta - \gamma^2}} [zU - (\lambda - U^2 - 8 \ln U)^{\frac{1}{2}}] \quad (z_* < z < m), \qquad (59)$$

which may also be written in terms of θ as follows:

$$\eta = \sqrt{\frac{\beta}{\epsilon(\beta - \gamma^2)}} \cdot \frac{1}{\sqrt{1 + z^2}} [z\theta + (1 - \theta^2 - \epsilon \ln \theta)^{\frac{1}{2}}] \quad (-k < z < z_*), \quad (60)$$

$$\eta = \sqrt{\frac{\beta}{\epsilon(\beta - \gamma^2)}} \cdot \frac{1}{\sqrt{1 + z^2}} [z\theta - (1 - \theta^2 - \epsilon \ln \theta)^{\frac{1}{2}}] \quad (z_* < z < m). \quad (61)$$

If we substitute for z from equations (51) and (52), complete expressions for η in terms of a single variable, θ, will be obtained. However, they are so complicated that they will not be presented here.

Equations (54), (55), (60), and (61) thus obtained, together with the auxiliary equations (51), (52), and (56), constitute the required analytical solution of the present diffusion problem—*i.e.*, the concentration-time-distance curve, with θ as an intermediate variable. The parameters ϵ and θ_m of these equations are evaluated by means of equations (44) and (50) as functions of k and m; and k and m, in turn, are computed by means of equations (28) from given values of the parameters β and γ.

One might conceive that the general expressions obtained avove should transform to the corresponding solutions presented in Parts I and II when the parameters β and γ have values such that the diffusion coefficient of the present work (equation (3)) reduces to equations (1) and (2), the diffusion coefficients of the previous papers. This transformation, however, cannot be made because of the limitations imposed with respect to these parameters (equations (16) and (17)). For example, when $a = -\lambda/2$ and $b = 0$, in which case equation (3) reduces to equation (1), $\beta = 0$ and $\gamma = \lambda C_o/2$, neither of the conditions (16) and (17) being satisfied. When $a = -\lambda$ and $b = \lambda^2$, in which case equation (3) reduces to equation (2), condition (17) cannot be satisfied, although condition (16) may be satisfied with a particular set of values of λ and C_o.

Despite such limitations to the parameters β and γ, it is possible to derive the corresponding solution for the case of a constant diffusion coefficient from the present general solution, if a limiting process in which both of the parameters β and γ are allowed to approach zero, retaining the conditions (16) and (17), is made for the general solution. The calculation is easy, although cumbersome in some points, so that only the result obtained will be presented here:

$$c = 1 - \text{erf } \eta, \quad (62)$$

which, as might have been expected, is the well-known solution for the unidimensional diffusion with a constant coefficient in a semi-infinite medium.

A Numerical Example

The various analytical expressions obtained in the preceding section are considerably complicated in form, and, in addition, contain two independent parameters which may be chosen arbitrarily, but at least within certain limitations. This apparently makes the numerical solution very cumbersome. However, if the numerical calculation for a well-chosen special case is carried out, an aspect of the general character of the diffusion process following the diffusion coefficient-concentration relationship given by equation (3) can be obtained.

The special case chosen for this numerical work is that in which the diffusion coefficient passes through a pronounced maximum in the middle portion of the concentration diagram, in accordance with the experimental diffusion coefficient behavior found by Robinson *et al.* [3, 9] and also by Long *et al.* [7] for some polymer-solvent systems.

Figure 3 shows the diffusion coefficient-concentration plot corresponding to $\beta = 2.935$ and $\gamma = 1.660$, the case for which the present numerical calculation has been performed. It may be seen that at a suitable intermediate concentration the diffusion coefficient reaches a considerably high maximum, which is about 17 times greater than the D value at zero concentration. Figure 4 represents

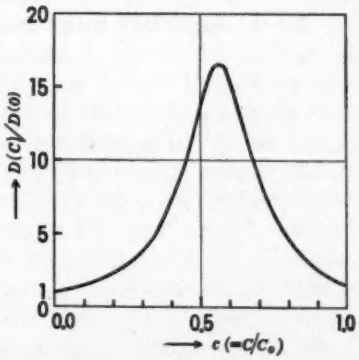

FIG. 3. *An example of the diffusion coefficient relation represented by equation (3); $\beta = 2.935$ and $\gamma = 1.660$, where $\beta = bC_o^2$ and $\gamma = -aC_o$.*

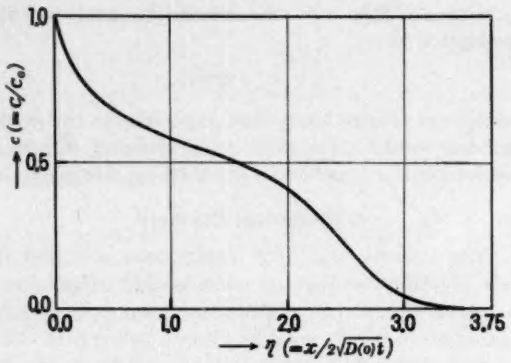

FIG. 4. *Calculated concentration-distance curve corresponding to the case of* D(C) *shown in Figure 3.*

the calculated concentration-distance curve, c plotted against η. The double-S shape of this curve should be noted, which is essentially in agreement with the schematic concentration-distance curve drawn by Hartley [6] for diffusion behavior in swelling high-polymeric solids. Partial qualitative agreement of our calculated curve with experimental curves has also been observed. However, it is beyond the scope of the present work to attempt a quantitative comparison between them, partly because of the great difficulty arising from the complexity of the mathematical solution, and partly because of a quantitative difference in the diffusion coefficients in both the theoretical and the above-mentioned experimental cases.

Acknowledgment

The author is indebted to Mr. A. Kishimoto of this laboratory for aid in the numercial calculations.

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Correction to Part II

In Part II of this series by Hiroshi Fujita (TEXTILE RESEARCH JOURNAL **22**, 823–7 (Dec. 1952)) equation (24) should be corrected to read: $\beta^2 = \frac{1}{2\mu}$.

A Study of Some Factors Affecting the Tear- and Water-Resistance of Lightweight Clothing and Tentage Fabrics*

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Abstract

Strength and water-resistance data are presented for a series of lightweight cotton fabrics varying in weave (wind-resistant twill and sateen), filling yarn type (60/2 combed and 30/1 carded), filling cover factor (15 and maximum), and finish (mercerized and unmercerized, both water-repellent-treated). The results indicate that the sateen has better tear strength than the wind-resistant twill but poorer water-resistance characteristics. The tighter weaves are less penetrable but more easily torn. The fabrics made of combed filling yarns are better than those made of carded filling yarns in both tear strength and water-resistance. Mercerization improves the tear strength but lowers the water-resistance, especially for the sateen weaves. Fire-resistant-treated sateen is shown by the data to have approximately twice the filling tear-resistance of fire-resistant-treated twill, with a somewhat lower, but still satisfactory, hydrostatic resistance.

Introduction

Cloth, Cotton, Wind-Resistant Twill, Type *I*, has been standardized for military procurements as a light weight wind- and water-resistant fabric for use in arctic tentage and clothing where the load carried by combat soldiers must be kept at a minimum in order that reasonable fighting efficiency may be maintained.

This fabric, a 2/2 twill normally having 185 ends and 92 picks of 2-ply combed cotton yarn, is very satisfactory in regard to wind- and water-resistance. However, it has long been considered necessary to increase its tear-resistance to prevent premature failure due to rips and tears in use. With the introduction of the use of fire-resistant treatments for the wind-resistant twill, in which form the cloth is used as the deck of the lightweight hexagonal tent, this problem has become particularly serious because of the further lowering in tear-resistance that occurs through the stiffening of the yarns in the fabric. The loss in tear-resistance due to the fire-resistant treatment frequently results in deliveries of fabric having less than 2-lb. resistance.

An obvious possible solution to this problem would be to use a fabric composed of inherently stronger synthetic fibers; however, most of the efforts to use a completely synthetic fabric, such as, for example, the nylon oxford, have not been rewarding. The difficulty of obtaining effective fire-resistance treatments for synthetics, alone or in combination with natural fibers, has not yet been overcome, and it has been necessary to redirect efforts towards the utilization of natural fibers in new designs so as to achieve a fabric satisfactory in all parameters for arctic use.

In recognition of the problem, the Quartermaster Laboratories with the cooperation of the National Research Council Subcommittee on Fiber and Fabrics initiated a study in Feb. 1951 on the effect of constructional and finishing factors on the tear-resistance of lightweight cotton fabrics in the range of 5.5 to 6.0 oz./yd.^{2}. The prime purpose of the investigation was to design a fabric construction which would be equivalent to the wind-resistant twill in water-resistance, but which would have a higher intrinsic tear-resistance, especially in the filling direction. Considered in the over-all study were the influence of weave, texture, spinning system, fiber type, and finishing variables, particularly mercerization. This report includes data only on the all-cotton construc-

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tion made by one mill.* The data illustrate the effect of the variables studied since all the fabrics were made from one cotton stock and the equipment used was constant throughout the experiment. Data from other mills that participated in this study as well as the results on the synthetic fiber filling will be reported at a later date.

Materials

A 72/2 combed cotton yarn warp was set aside for all the fabrics produced in this experiment. One half of the warp was woven into the 2/2 wind-resistant twill construction, and the other half was woven into a 5-harness, 2-counter right warp sateen. Two yarns, a 60/2 combed cotton and a 30/1 carded cotton, were used for the filling of both the twill and sateen weaves. The National Research Council Subcommittee recommended the warp and filling yarns which were chosen as both suitable and practical for the two weaves.

The fabrics were woven so as to have a total cover factor (finished) of approximately 45 since it has been found in a previous study [8] that this is the degree of tightness necessary for military rain-resistant materials. A warp cover factor of 30 was adopted as well suited for water-resistance. This was met by the twill fabric, 185 ends of 72/2 combed yarn, whose cover factor was calculated to be 30.9. The filling cover factor was then set at approximately 15.

Furthermore, in consideration of the variations that might exist between the ideal and the practical, additional constructions were made in which the highest practical number of picks was woven into the fabric regardless of the filling cover factor desired. This brought the total to eight fabrics, four having a filling texture corresponding to a theoretical cover factor of 15 and four having the maximum practicable filling texture. It was fortunate that this was done, because, as actually delivered, the fabrics designed to have a cover factor of 15 in the filling had somewhat less than this amount, whereas the tighter fabrics averaged just about the planned 15.

Finally, the eight fabrics were divided into two lots, one of which was subjected to all the normal finishing operations including mercerization, and the other finished without mercerization. Thus, a total of sixteen fabrics were produced and evaluated in this experiment.

As a final portion of this experiment, two of the sateen constructions were given the standard fire-

* J. P. Stevens and Co.

TABLE I. ACTUAL CONSTRUCTIONAL DETAILS OF LIGHTWEIGHT WATER-RESISTANT FABRICS

Fabric	Yarn count ($W \times F$)	Weight	Theoretical cover factor (Filling)	Actual texture ($W \times F$)	Actual cover factor W	Actual cover factor F	Finish‡
			Wind-Resistant Twill				
8A loose	72/2 × 60/2*	5.5	15	181 × 75	30.2	13.7	1
8B tight	72/2 × 60/2	5.7	max	181 × 86	30.2	15.7	1
8A–M loose	72/2 × 60/2	5.5	15	183 × 76	30.5	13.9	2
8B–M tight	72/2 × 60/2	5.8	max	184 × 85	30.7	15.5	2
9A loose	72/2 × 30/1†	5.5	15	179 × 78	29.8	14.2	1
9B tight	72/2 × 30/1	5.5	max	179 × 82	29.8	15.0	1
9A–M loose	72/2 × 30/1	5.5	15	182 × 76	30.4	13.9	2
9B–M tight	72/2 × 30/1	5.5	max	181 × 81	30.2	14.8	2
			Sateen				
1A loose	72/2 × 60/2*	5.6	15	183 × 80	30.5	14.6	1
1B tight	72/2 × 60/2	5.7	max	180 × 85	30.0	15.5	1
1A–M loose	72/2 × 60/2	5.6	15	183 × 80	30.5	14.6	2
1B–M tight	72/2 × 60/2	5.8	max	182 × 84	30.4	15.3	2
2A loose	72/2 × 30/1†	5.6	15	182 × 82	30.4	15.0	1
2B tight	72/2 × 30/1	5.8	max	180 × 88	30.0	16.1	1
2A–M loose	72/2 × 30/1	5.6	15	182 × 81	30.4	14.8	2
2B–M tight	72/2 × 30/1	5.6	max	183 × 87	30.5	15.9	2

* 60/2's combed yarn.
† 30/1's carded yarn.
‡ Finish 1: durable, water-repellent, vat 107-preshrunk, not mercerized. Finish 2: the same, but mercerized.

resistant treatment so that their performance characteristics could be compared to the standard fire-resistant-treated twill fabric. The actual constructional characteristics of the sixteen fabrics as delivered are summarized in Table I.

Test Methods

In selecting the test methods to be used in evaluating the fabrics, prime consideration was given to the evaluation of the critical tear- and water-resistance properties. Of the various methods available for evaluating tear-resistance, the simplest and most convenient to use is the Elmendorf test. This procedure uses a preslit specimen held between two clamping jaws, but differs somewhat from the more conventional tearing procedures such as the tongue and trapezoid in that it provides a measure of the energy required to tear a given distance of fabric rather than of the force required to continue a tear. In addition, the rate of application of the tearing force is much greater in the case of the Elmendorf test than in the trapezoid or tongue tests. Despite these apparently major differences in mechanism, previous work [5] indicates that the methods correlate very well and for many purposes can be used interchangeably. Besides the tear-resistance test, breaking strength measurements were made in order to obtain comparative rankings of the fabrics.

Past experience suggests that the conventional hydrostatic resistance test and the dynamic absorption test, while not infallible, do furnish a basis for making a realistic analysis of the probable field performance of water-resistant materials. These two tests were used to evaluate all the fabrics in this series, and most of the conclusions regarding water-resistance are based on analysis of the data from these tests. In addition, the spray and drop-penetration tests were performed. The spray test provides a convenient index of the effectiveness of the water-repellent treatment (surface repellency), and the drop-penetration test has been found, in the case of cotton fabrics, to correlate with rain penetration in simulated rainfall. Although there is an element of interpretation required in using this correlation, it has supporting value in assessing the relative performance of a group of fabrics such as are discussed herein.

Air permeability tests (Frazier) were made as a convenient measure of the wind-resistance of the fabrics. All of the tests were conducted as specified in Federal Specification, Textile Test Methods, CCC–T–191b [4].

Results and Discussion

A consolidation of the test data for the experimental fabrics is shown in Table II. In view of the great amount of information collected, the important variables studied are presented for comparison in separate figures. Accordingly, the results for a given fabric may appear in several places in the report.

Effect of Weave on Fabric Characteristics

The data presented in Table II illustrate the effect of weave on strength and resistance to water and wind. For a given set of yarns and textures, the weave type appears to have a most pronounced effect on the functional performance of the fabrics. The sateens consistently have higher tear-resistance, but lower breaking strength, lower hydrostatic resistance, lower drop-penetration time, and higher air permeability than the twills.

Figure 1 illustrates the magnitude of the differences between the sateens and the twills for three of the more significant tests used. The filling tear-resistance of mercerized fabrics made from equiva-

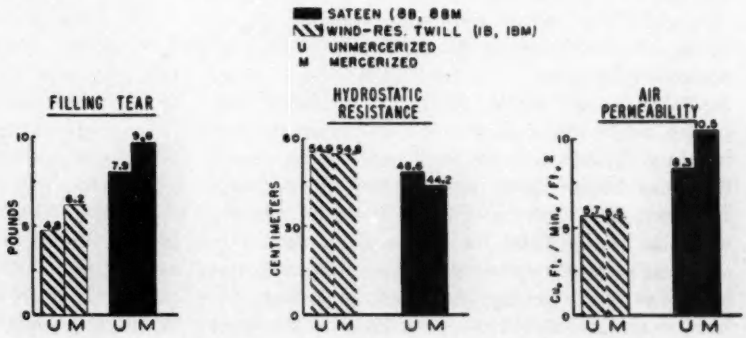

FIG. 1. *Effect of weave on fabric characteristics (high-textured fabrics, 60/2 combed filling yarns).*

TABLE II. EFFECT OF FABRIC CONSTRUCTION AND FINISHING ON FUNCTIONAL CHARACTERISTICS

STRENGTH

Wind-Resistant Twill					*Sateen*				
	Tear-resistance (lbs.)		Breaking strength (lbs.)			Tear-resistance (lbs.)		Breaking strength (lbs.)	
Fabric	Warp	Filling	Warp	Filling	Fabric	Warp	Filling	Warp	Filling
60/2 Filling					60/2 Filling				
8A loose	6.7	6.0	174	68	1A loose	8.5	8.1	145	64
8B tight	5.7	4.8	173	83	1B tight	7.4	7.9	152	62
8A–M loose	8.6	7.6	189	72	1A–M loose	10.2	10.2	160	60
8B–M tight	6.8	6.2	187	88	1B–M tight	9.3	9.8	165	67
30/1 Filling					30/1 Filling				
9A loose	5.6	2.6	161	37	2A loose	7.1	3.1	146	33
9B tight	6.4	3.1	168	44	2B tight	6.5	3.0	150	43
9A–M loose	7.6	3.3	181	43	2A–M loose	9.4	3.5	163	33
9B–M tight	6.5	2.7	186	41	2B–M tight	8.1	3.8	172	40

WATER AND WIND-RESISTANCE

Wind-Resistant Twill					*Sateen*				
Fabric	Hydrostatic resistance (cm.)	Dynamic absorption (%)	Drop penetration (min. to collect 10 ml.)	Air permeability (cu. ft./min./sq. ft.)	Fabric	Hydrostatic resistance (cm.)	Dynamic absorption (%)	Drop penetration (min. to collect 10 ml.)	Air permeability (cu. ft./min./sq. ft.)
60/2 Filling					60/2 Filling				
8A loose	51.0	18.8	12.4	8.0	1A loose	46.8	20.2	11.6	8.4
8B tight	54.9	18.9	19.4	5.7	1B tight	48.6	19.6	16.8	8.3
8A–M loose	48.9	16.8	9.1	9.3	1A–M loose	39.9	18.5	7.3	13.5
8B–M tight	54.8	16.9	17.4	5.5	1B–M tight	44.2	18.2	7.4	10.5
30/1 Filling					30/1 Filling				
9A loose	47.3	19.1	7.0	10.2	2A loose	45.1	20.1	4.3	13.2
9B tight	49.5	18.3	8.7	7.6	2B tight	44.1	20.2	8.6	11.8
9A–M loose	43.8	17.2	4.2	13.7	2A–M loose	39.3	18.1	3.8	21.4
9B–M tight	47.9	17.1	7.9	10.5	2B–M tight	39.7	18.4	4.8	18.2

lent plied yarns is increased from 6.2 lbs. to 9.8 lbs., or more than 58%, by changing the weave from the twill to the sateen. On the other hand, the hydrostatic resistance for the same fabric drops from 54.8 cm. to 44.2 cm., or approximately 19%, while the air permeability almost doubles, going from 5.5 to 10.5 cu. ft./min./sq. ft. This same trend is followed throughout the sateen and twill constructions, although the magnitude of the differences varies over a considerable range. For example, as may be noted in Table II and Figure 3, the fabrics made with carded single filling show much less of an increase in tear-resistance from the twill to the sateen weave than the fabrics made with combed plied filling. However, the values of Figure 1 appear, on the whole, to be typical for the fabrics as a group.

In analyzing the meaning of these data, it is important to assess the significance of the absolute differences that were observed. On the basis of current specification standards, it is fairly certain that the hydrostatic resistance of the sateen weave (even when mercerized) would easily meet minimum requirements for water-resistance. The air permeability of the sateen, on the other hand, is somewhat higher than is allowed in the specification for twill—*viz.*, 8.0 cu. ft./min./sq. ft.

The increase in tear-resistance, it may be added, is definitely significant, and will better enable the fabric to meet standards for tear-resistance dictated by field-performance requirements.

It is interesting to note that while the warp and filling tear-resistance of the sateen is significantly higher than that of twill, the breaking strength of the sateen is lower in all instances, ranging for comparable fabrics from 1 lb. to 29 lbs. less than the twills. As far as water-resistance is concerned, results of the hydrostatic pressure tests were confirmed by the drop-penetration tests. The dynamic absorp-

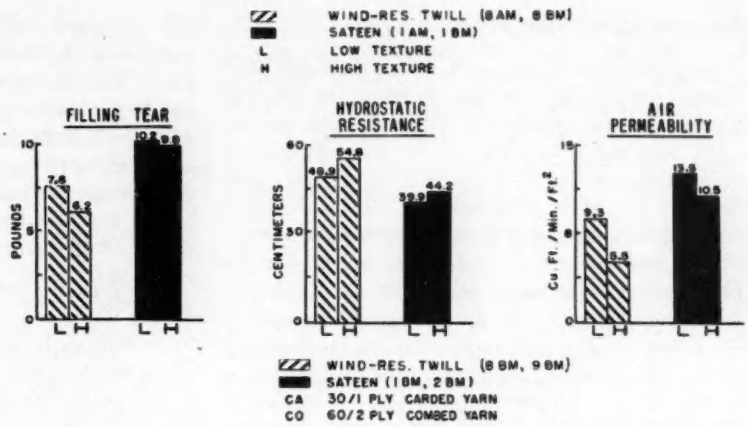

FIG. 2. *Effect of fabric tightness on fabric characteristics (mercerized fabrics, 60/2 filling yarns).*

FIG. 3. *Effect of filling yarn type on fabric characteristics (high-textured, mercerized fabrics).*

tion of the sateen-weave fabrics was approximately 1% higher than that of the twill-weave fabrics.

Effect of Tightness

The effect of fabric tightness on tear-resistance [7] and water-resistance [8] is well known and has previously been reported. The data obtained in this study confirmed the accepted concepts. As shown in Figure 2, increasing the tightness of the fabric by higher filling texture tends to produce a small decrease in the tear-resistance, increases the hydrostatic resistance, and decreases the air permeability. The low magnitude of the differences observed indicates that significant increases in the water-resistance of the sateen fabrics may be produced without an appreciable drop in tear-resistance by increasing fabric tightness. Thus, it is apparent that the best compromise for tear- and water-resistance in the sateen weave may be obtained by using as tight a construction as practicable. As might be expected, the increase in texture, while slightly reducing the tear-resistance of the fabric, did not adversely affect the breaking strength. In fact, in practically all instances, the filling tensile strength was increased in the higher textured fabrics.

The average change in performance produced by increasing the pickage in the twill constructions was an increase of 4.0 cm. in hydrostatic resistance, a decrease in air permeability of 2.9 cu. ft./min./sq. ft., and a decrease in average warp and filling tear-resistance of 0.7 lb. For the sateen constructions the corresponding changes were as follows: increase of 1.4 cm. in hydrostatic resistance, decrease of 1.9 cu. ft./min./sq. ft. in air permeability, decrease of 0.5 lb. in average warp and filling tear-resistance. For any given characteristic, the magnitude of the change produced by increasing the pickage is less in the case of the sateen. On a unit pick basis, however, the differences between the sateens and twills due to increased texture are considerably less. The average change per added pick results in an increase in hydrostatic resistance of 0.5 cm. for the twill and 0.3 cm. for the sateen; a decrease in air permeability of 0.4 cu. ft./min./sq. ft. for the twills and 0.4 cu. ft./min./sq. ft. for the sateens; a decrease in tear-resistance of 0.1 lb. per added pick for both cloths. It should not be assumed from the above that the changes noted per added pick are linear. Any attempt to design fabrics or to modify specifications based on the assumption of linearity of this relationship should be approached cautiously.

Effect of Filling Yarn Type

In making the comparison between the carded and combed yarn fillings, recognition should be given to the fact that the carded yarn was singles construction while the combed yarn was plied. Thus, differences in performance can be attributed to both of these factors. Figure 3 indicates that the carded-yarn fabrics have much lower filling tear-resistance, somewhat lower hydrostatic resistance, and higher air permeability. The lower tear-resistance results almost completely from the lower breaking strength of the filling yarns. The comparison of the breaking strength of the filling yarn and of the tear-resistance in the filling direction of the fabrics is shown in Table III, where tear-resistance is seen to be almost directly proportional to the yarn strength for each weave type.

The hydrostatic resistance of the fabrics was reduced approximately 5 cm. by the use of carded filling yarns. This reduction probably reflects the lack of uniformity of the carded yarn, which reduces the effective packing in the weave structure. This was confirmed by observation of light transmitted through the fabric, and is being verified further by pore-size determinations. Still, from the standpoint of hydrostatic resistance alone, it is likely that the carded-yarn fabrics would perform satisfactorily. The air permeability of the carded-yarn fabrics is approximately double that of the combed-yarn fabrics. This difference again is evidence of the inability to obtain close packing with the carded yarns, and also reflects the lower twist and lower tightness of the carded-yarn structure, which permits flow of air through the interfiber spaces.

Effect of Mercerization

Mercerization is known to have a profound effect on the physical and structural properties of cotton. The increase in strength and change in cross-sectional shape as well as the modified chemical affinities of mercerized cotton are bound to have an effect on the properties of interest for lightweight water-resistant fabrics. As shown in Figure 4 and Table II, the mercerized fabrics had consistently higher tear-resistance, lower hydrostatic resistance, and higher air permeability. It may also be noted, as shown in Table II, that the drop-penetration time was less for mercerized fabrics, yet the dynamic absorption was lower. The increase in tear-resistance of the mercerized fabrics reflects the increase in strength of the individual yarn resulting from the mercerizing process (Table IV). In addition, it has been noted [3] that mercerization modifies the surface characteristics of the yarn so as to lower yarn-to-yarn friction,

TABLE III. COMPARISON OF YARN BREAKING STRENGTH AND FABRIC TEAR-RESISTANCE OF HIGH-TEXTURED MERCERIZED FABRICS (FILLING)

Code	Fabric	Yarn	Yarn breaking strength (lb.)	Filling tear-resistance (lbs.)
8B–M	twill	60/2 combed	0.83	6.2
9B–M	twill	30/1 carded	0.37	2.7
1B–M	sateen	60/2 combed	0.81	9.8
2B–M	sateen	30/1 carded	0.37	3.8

TABLE IV. COMPARISON OF YARN BREAKING STRENGTH AND FABRIC TEAR-RESISTANCE OF HIGH-TEXTURED COMBED-YARN FABRICS (FILLING)

Code	Fabric	Finish	Yarn breaking strength (lb.)	Filling tear-resistance (lbs.)
8B–M	twill	mercerized	0.83	6.2
8B	twill	unmercerized	0.77	4.8
1B–M	sateen	mercerized	0.81	9.8
1B	sateen	unmercerized	0.71	7.9

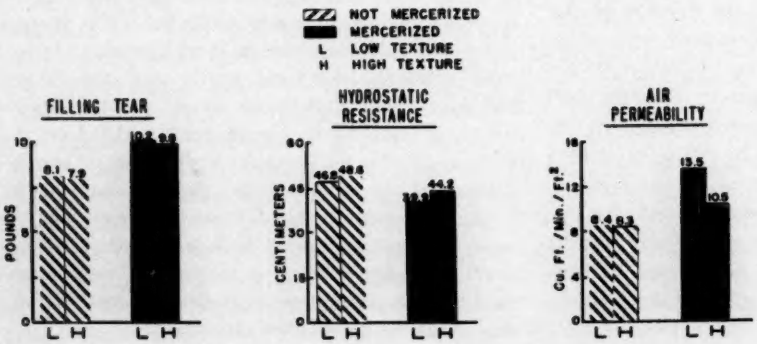

FIG. 4. *Effect of mercerization on fabric characteristics (60/2 yarns, sateen weave).*

increase the capacity of the fabric for distortion, and, as a result, increase the fabric's tear-resistance.

The increased affinity of mercerized fabrics for dyes is well known, and is the primary reason for much of the commercial mercerization of fabrics. Mercerization also causes an increased affinity for other fabric finishes. It has been noted, for instance, that it will yield a better water-repellent-treated fabric. This improvement is usually reflected in lower dynamic absorptions and sometimes higher spray ratings. However, this improved water-repellency does not normally act to increase the hydrostatic resistance or the drop-penetration time because of the changes in the physical and structural properties of the yarn that take place during mercerization. The probable rounding and smoothing of the yarn surfaces reduces the effective cover of the fabric, thus increasing the amount of void space through which water can pass in the hydrostatic-resistance and in the drop-penetration tests. The air permeability is increased because of the same phenomenon. In summary, the tear-resistance in the filling direction was increased on the average by 1.1 lbs. because of mercerization, while the corresponding decrease in hydrostatic resistance was 3.6 cm. and the increase in air permeability 3.7 cu. ft./min./sq. ft. As was pointed out in a preceding section (p. 243–4), the inferiority of the mercerized sateens with regard to water- and wind-resistance may not be overly serious.

Factors Entering in the Tear-Resistance of Lightweight Wind-Resistant Cotton Fabrics

Analysis of the preceding data indicates that all the factors considered—weave, yarn type, tightness, mercerization—have an effect on the tear-resistance of the fabric. Other workers have suggested additional contributing factors. In 1933 Schiefer [7] cited the importance of weave, yarn strength, and also fabric deformability on the tear-resistance of fabrics. More recently, the Fabric Research Laboratories [3] indicated the importance of crimp balance as a contributing factor to tear-resistance.

Given below is a list of such factors and a measure that could be used to assign a quantitative value to each one of these.

Constructional factor	Quantitative measure *
1. Weave	Weave factor
2. Yarn strength	Breaking strength of yarn
3. Deformability	Crimp balance
4. Lubricity	Yarn pull-out force

"Weave factor" was defined by Backer and Tanenhaus [2] as $\frac{\text{yarns/repeat of weave}}{\text{interlacings/repeat of weave}}$. For example, in a plain weave where there are 2 yarns per repeat and 2 interlacings per repeat, the weave factor would be 1. In a twill cloth with 4 yarns and 2 interlacings per repeat, the weave factor is 2. In the sateen with 5 yarns and 2 interlacings per repeat, the weave factor is 2.5. Other factors being equal, as the weave factor increases, the tear-resistance of the fabric will increase.

Yarn strength, as shown in Tables III and IV, contributes directly to the ultimate fabric tear-resistance. For a given fabric, the greater the individual yarn strength, the greater will be the resistance to tearing.

The Fabric Research Laboratories [3] suggested that a significant factor governing fabric deformability is the crimp balance of the yarns in the fabric. "Crimp balance" is defined as the ratio C_1/C_2, where C_1 is the smaller crimp numerically. If this value is for the filling direction, then C_2 refers to the warp crimp. The closer this ratio is to 1, the higher will be the tear-resistance of the fabric. The values of crimp balance and tear-resistance for the high-textured unmercerized fabrics studied are noted in Table V.

Yarn lubricity is the ease with which one set of yarns can move over the other in the fabric. Yarn pull-out tests [3] indicated that mercerization increases lubricity by reducing the yarn-to-yarn friction, and accordingly lowers the yarn pull-out force. In addition to mercerization, such finishing agents as water-repellent waxes will increase lubricity, while

TABLE V. COMPARISON OF CRIMP BALANCE AND FABRIC TEAR-RESISTANCE OF HIGH-TEXTURED UNMERCERIZED FABRICS

Code	Fabric	Filling yarn	Crimp balance	Tear-resistance ($W \times F$) (lbs.)
8B	twill	60/2 combed	0.56	5.7 × 4.8
9B	twill	30/1 carded	0.71	6.4 × 3.1
1B	sateen	60/2 combed	0.76	7.4 × 7.9
2B	sateen	30/1 carded	0.69	6.5 × 3.0

* Some of the measures may be used to evaluate more than one factor.

some resins will decrease this property. High lubricity as measured by the pull-out force leads to greater tear-resistance.

In addition to showing lubricity, the yarn pull-out test results also reflect crimp balance and weave factor. Thus, the yarn pull-out test can be used to determine the over-all deformability of the fabric, which is related to its tear-resistance.

It has been found that dividing the average yarn strength by the average pull-out force for the opposite set of yarns gives a factor which is directly related to the actual Elmendorf tear test values for the fabrics under discussion. Table VI and Figure 5 show this relation, which gives a good indication of the importance of the constructional and finishing factors for the tear-resistance of lightweight cotton fabrics of this type.

Hydrostatic Resistance and Air Permeability

The mechanism of transfer of fluids through fabric structures is not very well understood at the present time. Some work has been done on gas transfer, and a recent paper by Backer [1] relates the geometry of fabric interstices to air flow and summarizes some of the findings regarding the role of fabric structure in air permeability. Even less work has been done on liquid transfer through fabrics. Much of what has been published stresses the importance of fabric tightness and thickness for resistance to water penetration. Table VII shows how the factors studied here affect the air permeability and hydrostatic resistance of the fabrics. The magnitude and direction of the effects are indicated.

As expected, all the parameters which increase hydrostatic resistance (less porosity) also decrease air permeability (less porosity). It is logical to assume that the sateen-weave fabrics should be more permeable than the twill-weave fabrics, since the former have longer float lengths through which the fluid may disperse and are also more subject to distortion.

The effect of tightness is well understood, and among all the factors of fabric construction the relative tightness has the most pronounced significance for fluid penetration. The effect noted for the mercerized fabrics and carded *vs.* combed yarn was explained in preceding sections (pp. 246–7). In a

TABLE VI. CORRELATION BETWEEN THE QUOTIENT OF YARN STRENGTH DIVIDED BY OPPOSITE YARN PULL-OUT FORCE AND ELMENDORF TEAR-RESISTANCE DATA

Sample No.	Weave	Quotient Yarn strength / Yarn pull-out force W	F	Elmendorf tear-resistance W	F
Unmercerized					
8B	2/2 twill	3.3	2.6	5.7	4.8
9B	2/2 twill	2.9	1.4	6.4	3.1
1B	5 harness sateen	4.9	5.2	7.4	7.9
2B	5 harness sateen	4.7	2.2	6.5	3.0
Mercerized					
8B–M	2/2 twill	3.9	3.0	6.8	6.2
9B–M	2/2 twill	3.6	1.6	6.5	2.7
1B–M	5 harness sateen	5.9	8.2	9.3	9.8
2B–M	5 harness sateen	4.2	2.9	8.1	3.8

Correlations Warp: $r = .81$
Filling: $r = .95$

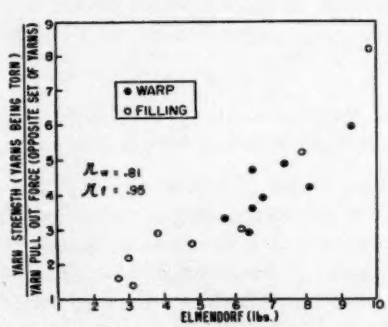

FIG. 5. *Tear-resistance as a function of yarn strength and yarn pull-out force.*

TABLE VII. FACTORS AFFECTING FLUID PENETRATION THROUGH LIGHTWEIGHT WIND-RESISTANT FABRICS *

Factor	Hydrostatic resistance: Direction of change	Hydrostatic resistance: Ave. change (cm.)	Air permeability: Direction of change	Air permeability: Ave. change (cu. ft./min./sq. ft.)
Weave (high weave factor)	decreases	6.3	increases	4.4
High tightness	increases	0.5 per added pick	decreases	0.4 per added pick
Mercerization	decreases	3.5	increases	3.6
Carded *vs.* combed	decreases	4.1	increases	4.6

* Figures are based on the average of all pertinent fabrics.

previous experiment [6] it had been noted that carded yarns will produce fabrics with somewhat lower air permeability because of the increased coverage afforded by the random distribution of fibers at the surface of the yarns. In the present experiment, however, it is likely that the unevenness of the carded yarn and the poorer packing that resulted offset any possible benefits of this random effect and led to higher air permeability.

Figure 6 illustrates the relative effect of some of the factors cited above on fluid penetration through the fabrics. It is of interest that fluid penetration decreases with increased filling texture more rapidly in the case of mercerized than in unmercerized fabrics, and more markedly in the mercerized sateen than in the mercerized twill. This applies to both the hydrostatic resistance and the air permeability.

Effect of Fire-Resistant Treatment

A standard fire-resistant treatment was applied to the low- and high-textured mercerized combed sateen fabrics. The treatment used consisted of a two-bath application in which the fire-retardant Erifon (an aqueous solution of inorganic salts containing free hydrochloric acid, the active flame-retarding salts being those of titanium and antimony) was topped with a mixture of G4 (dihydroxy dichloro diphenyl methane, a mildewcide) and a wax-emulsion water-repellent. The amount of water-repellent initially applied did not provide sufficient hydrophobicity to the fabrics, and it was necessary to re-treat with additional wax-emulsion.

Data showing the physical properties of the two treated sateen fabrics compared to two standard fire-resistant-treated twill fabrics are given in Table VIII.

The fire-retardant treatment decreased the tear-resistance of the sateen by somewhat more than 50%. The dynamic absorption of the two sateens was greatly increased, especially in the case of the high-textured fabric, indicating poor water-repellent treatment. It appears that the plugging of the fabric interstices with the fire-retardant compound was sufficient to keep the hydrostatic resistance of the low-textured fabric about the same in spite of the increase in absorption. In the case of the high-textured fabric, however, a decrease in hydrostatic resistance accompanied the increased absorbency. The air permeability was decreased probably also because of the filling of the interfiber spaces with treating compound. On the whole, with the exception of hydrostatic resistance, the properties of the treated sateens compare favorably with those of the twills, and the sateens have the great advantage of being twice as strong as the twills in filling tear-resistance in spite of the strength reduction caused by the treatment.

Conclusions

1. A laboratory study of the performance characteristics of lightweight water- and wind-resistant fabrics indicates that a 5.8-oz., high-sley, 5-harness sateen fabric, made of combed plied yarns and mer-

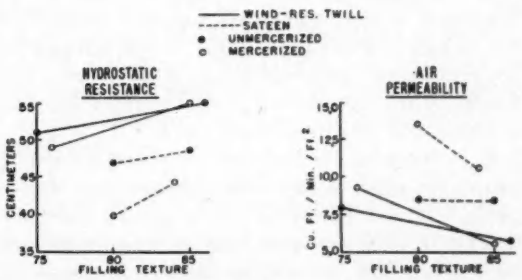

FIG. 6. *Relationship between fabric tightness and permeability of plied-filling-yarn fabrics.*

TABLE VIII. PROPERTIES OF FIRE-RESISTANT-TREATED TWILL AND SATEEN

	Wind-resistant twill from QM stock		Sateen	
	I	*II*	Low textured (Fabric 1A–M)	High textured (Fabric 1B–M)
Weight (oz./sq. yd.)	5.8	6.5	6.7	6.8
Texture ($W \times F$)	188×95	194×99	180×79	184×85
Tear-resistance (lbs.) Warp	3.0	3.2	4.6	4.4
Filling	1.8	1.9	4.2	3.9
Breaking strength (lbs.) Warp	156	203	190	196
Filling	71	92	88	96
Spray rating	80	80	90	90
Hydrostatic resistance (cm.)	49	52	40	40
Dynamic absorption (%)	26.4	24.0	25.6	27.3
Air permeability (cu. ft./min./sq. ft.)	7.9	5.6	4.9	3.2

cerized, will be a satisfactory replacement for wind-resistant twill fabrics in situations requiring higher tear-resistance.

2. Analysis of the effect of some structural and finishing variables on fabric performance indicates that:

(*a*) The sateen-weave fabrics have significantly higher tear strength, slightly lower hydrostatic resistance, and higher air permeability than twills of equivalent texture.

(*b*) Tightening the weave of fabrics by increasing the filling texture lowers the tear strength, increases the hydrostatic resistance, and lowers the air permeability.

(*c*) Combed-filling-yarn fabrics of the type used in this study have considerably higher tear strength, somewhat higher hydrostatic resistance, and lower air permeability than corresponding carded-filling-yarn fabrics.

(*d*) Mercerization increases the tear strength, decreases somewhat the hydrostatic resistance, and increases the air permeability of the fabrics studied. The effect of mercerization on hydrostatic resistance and air permeability is more pronounced in the sateen weave than in the twill weave.

3. In agreement with findings reported in the literature, it was found that the tear strength of the fabrics is intimately related to the strength of the component yarns, the weave of the fabrics, and factors related to ease of fabric deformability such as crimp and/or yarn pull-out force.

4. A standard fire-resistant treatment applied to two of the experimental sateen constructions appreciably decreased the tear strength and decreased the hydrostatic resistance and the air permeability of the fabrics. The fire-resistant sateens were superior to the standard fire-resistant-treated twills in tear strength and air permeability, but were inferior in hydrostatic resistance.

Acknowledgments

The fabrics produced for this study were designed jointly by a committee composed of Quartermaster Corps representatives and an *ad hoc* National Research Council Subcommittee on Fibers and Fabrics. Appreciation is expressed to the members of this committee and to the companies which they represent for their active participation and assistance in this study. The particular fabrics reported here were manufactured by J. P. Stevens & Co., and we are particularly indebted to them and to Mr. Joseph Meierhans for their active cooperation. Success would have been impossible without the outstanding leadership provided by Mr. Rudolph Semmler, chairman of the committee, whose efforts were invaluable in interpreting the various aspects of this study. Acknowledgment is also made to Dr. R. G. Stoll, previously of the Quartermaster Corps Laboratories, who assisted in the initial design of the fabrics.

Most of the measurements reported were performed by Mr. Charles Sembach of Textile Materials Engineering Laboratory. The tests on the fire-resistant-treated fabrics were performed in the Functional Finishes Laboratory under the supervision of Mr. Allan J. McQuade.

The assistance of Mr. John Medernach in the preparation of the graphs and of Dr. Oscar Mandel for the editorial review of this report is appreciated.

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Correlation of Yarn Strength with Fiber Strength Measured at Different Gage Lengths*

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Abstract

The fiber strengths of 105 cottons measured with the Clemson Flat Bundle Tester at 0, 2, 4, 6, and 8 mm. gage length were correlated with the strength of yarns made from the same cottons.

The correlation between single end yarn strength and flat bundle fiber strength was higher for all of the longer gage lengths than for so called zero gage length, being highest for 2 and 4 mm. For these gage lengths the coefficients of correlation ranged from 5% to 27% higher than for zero length for the several types and numbers of yarn.

The correlations for the skein strength favored the longer gage lengths even more than in the single end breaks, the coefficients ranging from 3% to 49% higher for 2 to 4 mm. gage lengths than for zero length. The results indicate that the increase in correlation with greater gage length, up to 4 mm., is higher the finer the yarns and also higher for combed yarns than for carded yarns.

From the tests it seems that the "equivalent gripping distance" on individual fibers in yarn breaks must be approximately 3 mm. and that measuring the fiber strength at the short lengths used in the Pressley test will incorrectly rank certain cottons in relation to their merit in yarns.

SEVERAL different researchers [3, 4, 5, 6, 7, 11] have reported that the very short gage length † used in the Pressley flat-bundle test is too short to give the best evaluation of the fiber. They have reported results showing that fiber strengths measured at longer gage lengths correlated better with the strength of yarns made from the same cottons. Other researchers have reported data that seemed to refute the above contention and show the usual Pressley test correlated best with actual yarn strengths.

From the geometry of a yarn and the mechanics involved in the yarn break, it would seem very surprising if the fibers broke as if they were gripped at points so close together as is the case in the Pressley test [2].

It is well known that some cottons lose strength more rapidly with increase in gage length than others, so it is important to know what is the equivalent "gripping length" as fibers are broken in a yarn. Possibly some cottons rated lower on the Pressley test and discarded should have been retained since they would make stronger yarns than some rating higher by the Pressley test. This is such an important thing to know it is strange it was not thoroughly investigated before generally accepting the Pressley test. Since there is so much difference of opinion this project was set up to at least give more data on the question.

Plan of Work and Cottons Studied

The program was of two parts. First, flat bundle strengths at five gage lengths and single strand yarn strengths were to be measured on 75 cottons on which the Production and Marketing Administration of the U.S.D.A. at Clemson, South Carolina, and College Station, Texas, had made skein strengths. The raw cotton and the yarns, with the exception of two samples, were furnished by the Bureau of Plant Industry, Soils and Agricultural Engineering. The remaining two samples were furnished directly by the Production and Marketing Administration. In the second part of the study fiber strengths at five gage lengths and yarn strengths on singles, plied, and tire cords were measured for 30 different cottons. Ten of these cottons were furnished by the Bureau of Plant Industry, the remainder by the Southern

* A report of work done under contract with the U. S. Department of Agriculture and authorized by the Research and Marketing Act of 1946. The contract is being supervised by the Southern Regional Research Laboratory of the Bureau of Agriculture and Industrial Chemistry.

† Gage length here refers to the distance between the inside faces of the jaws.

Regional Laboratory. These yarns were made in the Clemson School of Textiles in low, medium, and high twist multipliers. The fiber strengths at each gage length were to be correlated with skein strengths and single end strengths in every different yarn number and type of yarn.

Measurements

To make the study as valuable as possible, all fiber measurements were run by one man making all the breaks and another man preparing all the samples from the cottons after they had been run through the fiber blender developed by the Production and Marketing Administration of the U.S.D.A. These operators worked for two weeks on other cottons to thoroughly standardize their procedures before beginning the project.

The breaks were all made with the same set of jaws on the Clemson Flat Bundle Tester [9]. Each cotton was run at all five different gage lengths (0, 2, 4, 6, and 8 mm.) before going to the next cotton so that the tests on each cotton at the several gage lengths should be under essentially identical conditions. This was possible due to the fact that on the Clemson tester the gage length can be changed instantaneously. The jaws required replacement of leather faces only once during the project. All tests were run at closely controlled standard atmospheric conditions and corrected to measurements made on a check lot cotton which was run before each test cotton. Ten breaks were made on each cotton at each gage length instead of the usual six. Table I shows the equivalent Pressley index for these measurements. The Pressley indices for the longer gage lengths were reduced to be equivalent to the zero gage length level. This was done by dividing the actual mean breaking force in pounds by the specimen weight in milligrams and dividing the resulting value by the ratio of specimen length at zero gage length to specimen length at the longer gage length. The single end tests on all the yarns were also made by two men on the IP2 machine following A.S.T.M. Standards [1]. Twenty-five breaks were made on each yarn. Table II shows, for the first 75 cottons, the strengths and elongations to break with the standard errors of measurement.

The other 30 cottons were processed by the School of Textiles into the following yarns: 14/1—S Twist at optimum twist multiple and two other twists, one higher and one lower than optimum; 14/3—Z Twist plied yarns from each cotton; 14/3/3—S Twist cord from each cotton. Organizations and machine setting recommended by the U.S.D.A. Laboratory at Clemson [10] were used throughout. The tests on these cottons were run in exactly the same manner as for the first 75 cottons. Table III shows the results for these measurements.

The correlation coefficients between flat-bundle strength and yarn strength for single end breaks and skein breaks were computed for every different size and type of yarn by use of the following formula:

$$r = \frac{N(\Sigma xy) - \Sigma x \Sigma y}{\sqrt{[N(\Sigma x^2) - (\Sigma x)^2][N(\Sigma y^2) - (\Sigma y)^2]}}.$$

The actual work was done on a calculating machine that automatically gave Σx, Σy, Σx^2 and Σy^2 simultaneously, which increased the accuracy of the work. All computations were rechecked by a second operator. Of course, from the above data any coefficient given in the table may be recomputed. For the first 75 cottons the skein strengths had been measured in the government laboratories and these published values [8] were used in computing the correlations.

The data in Table I can be graphically shown by plotting fiber strength indices against gage length. Figure 1 shows the data for several cottons. The numbers on the curves refer to the corresponding cottons. The average standard error for the breaks on all cottons at each gage length are shown in Table IV.

Graphs are used to summarize the correlation between yarn strength and fiber strength at various gage lengths by plotting the correlation coefficients for each type or size of yarn against the gage lengths used in the fiber tests. Figures 2 to 6 inclusive show these correlation summaries.

Discussion of Results

It is believed that the measurements are rather precise as is shown by the smallness of the standard error on the various measurements. It should be recalled that the flat-bundle tester was used only to compare the strength of the several cottons with a check lot cotton which, according to other tests in the laboratory, was known to remain very constant. It is interesting that the standard error for the strength tests is less for longer gage length. Of course, smaller values are expected on smaller mean values, but it is seen that even when reduced to per-

TABLE I. FLAT BUNDLE FIBER STRENGTH AT DIFFERENT GAGE LENGTHS

Cotton lot no.	Variety	0 mm.	2 mm.	4 mm.	6 mm.	8 mm.
1	Acala 44 Pima 32 F1 Mixture	8.90	6.87	6.05	5.50	5.10
2	Acala 4-42	7.51	4.73	3.77	3.58	3.25
3	Pima 32 (Test #2)	10.03	7.37	6.61	5.92	5.48
4	F1(A44×P .32) Planted	8.38	6.05	5.44	5.10	4.95
5	Mesilla	8.13	4.96	4.32	4.02	3.81
6	Sea Island 185	9.22	6.52	6.13	5.49	5.30
7	Tanguis	7.71	4.77	4.16	3.78	3.38
8	AHA×Coker 100-50-255	7.65	4.74	4.14	3.73	3.49
9	Sealand 542	8.17	5.42	4.70	4.34	4.12
10	458-11	10.21	6.88	5.82	5.29	4.67
11	Sea Island St. Vincent	7.98	5.05	4.75	4.31	4.19
12	Watson Meban	5.85	3.62	3.26	2.96	2.80
13	Acala P 18C	6.47	4.33	3.80	3.51	3.29
14	Stormproof #1	7.10	3.90	3.29	*	*
15	Stoneville 62	7.64	4.02	3.15	2.85	*
16	Delfos 7343	7.68	4.35	3.97	3.61	3.37
17	Acala 44 Pima 32 F1	8.58	6.49	5.98	5.54	5.10
18	Empire	7.29	3.96	3.44	3.00	2.97
19	Rowden 41B 100	7.26	4.46	3.70	3.24	2.99
20	Deltapine 15	7.64	4.99	4.32	3.84	3.68
21	Karnak	8.83	6.04	5.65	5.35	4.82
22	6-1-5-10	8.77	5.41	4.57	3.97	3.51
23	Hopi Acala 50	9.07	5.40	4.24	3.84	3.70
24	13-40 Test	8.71	6.30	5.61	5.29	5.07
25	126-S-1	8.82	7.01	6.38	6.12	5.77
26	Acala 1517	7.86	4.76	4.17	3.83	3.56
27	Coker Wilds	7.76	4.93	4.63	4.23	4.00
28	Sea Island 195	8.99	5.99	5.28	5.01	4.61
29	T.H. D-27	10.50	7.04	5.90	4.91	4.41
30	A×D Test No. 4	7.43	5.02	4.24	3.74	3.60
31	1517 RB Test No. 4	8.30	5.13	4.33	3.97	3.56
32	Acala 4-42 Test No. 4	8.02	4.75	4.55	4.04	3.70
33	Acala 44 Arizona	7.54	4.78	4.25	3.67	3.44
34	Acala 33 Arizona 33	7.75	4.25	4.25	3.78	3.28
35	Acala 28 Arizona 28	7.29	4.82	4.17	3.90	3.59
36	Deltapine 15	6.71	4.17	3.75	3.49	3.28
37	CR3	7.63	4.52	3.74	*	*
38	Lockett 140	7.56	4.03	3.29	*	*
39	Lankart 57	7.20	4.69	3.88	3.42	3.14
40	Deltapine 15	7.68	4.83	4.04	3.84	3.34
41	Empire	7.89	4.50	3.44	3.02	2.72
42	Hibred	7.63	4.16	3.68	3.36	3.06
43	Paymaster	7.19	4.51	3.68	3.37	*
44	D & PL Fox	6.93	4.12	3.45	3.17	2.70
45	NR 13-10-1	7.90	4.74	4.26	3.74	3.23
46	Bobshaw 1A	9.32	5.11	4.10	3.52	3.16
47	Delfos 9169	7.51	4.53	4.13	3.72	3.56
48	Empire	8.46	5.01	4.42	3.81	3.56
49	DPL Fox	7.84	4.43	4.05	3.68	3.37
50	Stoneville 2B	8.10	4.50	3.82	3.57	3.27
51	Coker 100 WR	7.97	4.94	4.28	3.81	3.77
52	HAO	9.03	5.31	4.70	4.14	3.79
53	ACO	7.97	4.61	3.88	3.56	3.35
54	MEO	5.82	3.17	2.99	2.78	2.62
55	SDO	8.62	5.77	5.12	4.70	4.47
56	TSO	6.90	4.11	3.37	3.14	2.92
57	RNO	7.87	4.33	3.55	3.28	3.05
58	HAA	8.56	4.74	4.27	3.74	3.40
59	HAM	7.41	4.00	3.55	3.12	2.89
60	HAS	8.53	5.20	4.59	4.16	3.64
61	HAT	8.24	5.23	4.34	4.04	3.65
62	HAR	8.54	4.87	4.18	3.73	3.36
63	ACM	6.92	4.28	3.74	3.24	3.06
64	ACS	8.63	5.06	4.40	4.05	3.92
65	ACT	7.22	3.93	3.59	3.17	3.01
66	ACR	7.89	4.37	3.72	3.29	3.10
67	MES	7.94	5.29	4.72	4.12	3.89
68	MET	6.30	3.57	3.21	2.96	2.80
69	MER	6.76	3.54	3.13	2.78	2.62
70	SDT	8.28	4.98	4.47	4.01	3.70
71	SDR	8.30	5.03	4.50	4.23	3.79
72	TSR	6.83	3.84	3.50	3.12	2.83
73	Watson Mebane	5.90	3.58	3.26	3.03	2.89
74	Rowden	7.61	4.42	3.81	3.37	3.07
75	Deltapine	7.06	4.42	3.83	3.33	3.12
76	Acala 1-23-11-3	6.37	4.04	3.59	3.30	3.16
77	Bobshaw	7.77	4.37	3.71	3.38	3.05
78	Dixie Triumph	6.49	3.71	3.10	2.85	2.83
79	Empire	6.88	4.04	3.40	3.03	2.80
80	Tangelis	7.68	4.88	4.27	3.74	3.57
81	Wilds	8.03	5.05	4.48	3.96	3.62
82	Wilds	8.05	5.12	4.17	3.94	3.57
83	Iquitos Peruvian	6.87	4.30	3.54	3.26	3.00
84	Coker Wilt	6.84	4.08	3.42	2.99	2.81
85	Stoneville 2B	6.84	3.74	3.19	2.87	2.76
86	Delfos	6.18	3.95	3.36	3.05	3.02
87	Acala Hopi Acala	8.33	5.03	4.34	3.94	3.78
88	Rowden	7.09	4.16	3.58	3.19	2.96
89	Rowden	7.42	4.40	4.01	3.54	3.23
90	Empire	6.50	3.88	3.36	3.11	2.80
91	Lockett	6.66	3.93	3.39	*	*
92	Stoneville 2B	7.19	3.94	3.25	2.99	2.65
93	Deltapine 15	6.94	4.45	3.86	3.61	3.44
94	Delfos	7.26	4.28	3.57	3.18	3.05
95	Pima 32 Gizd.×Pima	9.66	6.78	5.85	5.54	5.15
96	68-63	8.35	5.12	4.41	4.12	3.81
97	Deltapine 15	6.71	4.17	3.75	3.49	3.28
98	Coker 100 WR	6.81	4.22	3.51	3.36	3.14
99	Hopi Acala 50	9.07	5.40	4.24	3.84	3.70
100	Fox	6.37	4.08	3.43	3.18	2.93
101	Acala 4-42	7.51	4.73	3.77	3.58	3.25
102	Triple Hybrid 458	10.21	6.88	5.82	5.29	4.67
103	Hopi Acala 46-124	9.10	5.84	4.86	4.25	4.07
104	EH 808	8.30	4.90	4.45	3.99	3.80
105	Acala 1517	7.86	4.76	4.17	3.83	3.56

TABLE I—*Continued*

* Too short.

* Too short.

TABLE II. SINGLE END STRENGTHS AND ELONGATIONS

Serial #	Yarn	Elongation means (%)	Strength means (g.)
1	22	7.08	644
	36	7.06	405
	36*	6.83	332
	60*	7.04	223
2	22	6.30	436
	36	6.28	277
	36*	6.22	264
	60*	5.71	159
3	22	7.36	594
	36	6.06	339
	36*	5.99	376
	60*	6.20	232
4	22	7.36	554
	36	7.20	344
	36*	7.62	396
	60*	6.62	218
5	22	6.87	479
	36	6.96	303
	36*	6.64	329
	60*	6.64	191
6	22	6.43	560
	36	5.72	335
	36*	6.16	380
	60*	5.16	193
7	22	7.58	378
	36	6.43	196
	36*	6.86	236
	60*	6.20	146
8	22	5.88	440
	36	5.18	246
	36*	5.62	267
	60*	5.06	166
9	36	5.67	289
	50	5.76	203
	36*	5.68	321
	60*	5.90	198
10	22	5.98	599
	36	5.52	340
	36*	5.90	416
	60*	5.45	240
11	22	7.25	535
	36	6.56	289
	36*	7.29	328
	60*	6.82	209
12	22	8.05	340
	36	7.31	196
13	22	8.56	400
	36	7.94	234
14	22	6.74	364
	36	6.16	191
15	22	6.82	388
	36	5.86	215

* Combed yarns.

TABLE II—*Continued*

Serial #	Yarn	Elongation means (%)	Strength means (g.)
16	22	7.52	454
	36	6.49	244
17	22	7.89	598
	36	8.05	337
	36*	9.01	435
	60*	7.94	235
18	22	7.04	430
	36	6.79	253
19	22	6.56	366
	36	6.00	211
20	22	6.79	441
	36	6.64	267
21	22	6.76	584
	36	6.60	355
	36	6.85	356
	36*	6.60	385
	60*	5.81	204
	60*	5.96	205
22	22	6.34	506
	36	5.59	303
	36*	5.78	305
	60*	5.10	175
23	22	5.92	506
	36	5.22	271
	36*	5.50	326
	60*	5.03	186
24	22	7.19	563
	36	6.67	345
	36*	6.78	396
	60*	6.15	212
25	22	7.14	607
	36	6.95	363
	36*	7.27	385
	60*	6.65	221
26	22	7.14	497
	36	6.58	284
	36*	7.32	320
	60*	6.43	172
27	22	6.80	487
	36	6.01	275
	36*	7.09	321
	60*	6.47	181
28	22	6.21	575
	36	5.70	322
	36*	5.48	370
	60*	5.94	210
29	22	6.29	610
	36	5.77	370
	36*	5.57	401
	60*	4.97	210
30	22	7.23	443
	36	6.46	234

* Combed yarns.

TABLE II—*Continued*

Serial #	Yarn	Elongation means (%)	Strength means (g.)
31	22	6.74	478
	36	6.71	284
32	22	6.85	454
	36	6.82	273
33	22	7.14	462
	36	6.73	269
34	22	6.66	464
	36	6.20	276
35	22	8.05	480
	36	6.88	253
36	22	8.65	405
	36	8.07	224
37	22	6.71	361
	36	6.00	189
38	22	6.77	382
	36	5.90	218
39	22	7.72	388
	36	7.00	220
40	22	6.79	388
	36	6.19	202
41	22	7.23	414
	36	6.59	220
42	22	6.86	367
	36	6.29	197
43	22	7.72	408
	36	7.09	229
44	22	7.43	416
	36	6.72	238
45	22	6.27	417
	36	5.74	241
46	22	5.58	456
	36	5.28	265
47	22	6.85	433
	36	7.01	265
48	22	7.16	486
	36	6.56	253
49	22	6.99	439
	36	6.65	266
50	22	6.79	464
	36	6.10	247
51	22	6.60	448
	36	6.54	256
52	22	6.56	550
	36	5.41	306

TABLE II—*Continued*

Serial #	Yarn	Elongation means (%)	Strength means (g.)
53	22	6.64	482
	36	6.34	299
54	22	7.66	356
	36	7.56	216
55	22	6.75	523
	36	6.10	300
56	22	7.89	385
	36	6.84	209
57	22	6.50	403
	36	6.29	228
58	22	6.57	504
	36	5.92	310
59	22	6.81	444
	36	6.56	251
60	22	6.82	502
	36	6.28	309
61	22	6.37	433
	36	6.04	249
62	22	6.05	488
	36	5.81	269
63	22	6.41	397
	36	6.15	235
64	22	6.70	531
	36	5.84	269
65	22	7.14	437
	36	7.06	250
66	22	6.55	446
	36	6.38	237
67	22	7.02	442
	36	6.78	250
68	22	8.01	392
	36	7.04	217
69	22	7.36	367
	36	7.23	227
70	22	7.16	459
	36	6.61	254
71	22	6.25	463
	36	5.65	265
72	22	7.08	363
	36	6.46	202
73	22	8.26	337
	36	7.76	196
74	22	7.53	413
75	22	7.85	448

TABLE III. SINGLE END STRENGTHS OF YARNS MADE IN TEXTILE SCHOOL FROM 30 COTTONS

Serial no.	Twist multiplier	14/1 S-twist Strength (25 breaks) Means (g.)	Std. error (g.)	14/3 Z-twist Strength (25 breaks) Means (lbs.)	Std. error (lbs.)	14/3/3 S-twist Strength (25 breaks) Means (lbs.)	Std. error (lbs.)
76	3.25	644	10.31	5.58	.082	18.26	.139
	3.75	651	9.37	5.31	.070	17.23	.232
	4.25	614	13.37	4.80	.082	16.10	.291
77	3.25	599	8.04	6.31	.084	20.51	.188
	3.75	626	9.43	5.83	.069	19.04	.362
	4.25	646	11.90	5.33	.074	17.87	.223
78	3.50	602	10.55	5.03	.062	16.27	.187
	4.00	610	10.02	4.83	.076	15.83	.213
	4.50	605	11.22	4.67	.066	15.04	.182
79	3.25	578	7.86	5.51	.071	17.72	.218
	3.75	575	10.02	5.16	.077	16.29	.266
	4.25	596	12.65	4.69	.071	15.64	.254
80	3.00	640	11.43	5.93	.081	18.76	.208
	3.50	687	15.20	5.95	.079	18.85	.187
	4.00	675	10.14	5.56	.069	18.16	.169
81	2.75	682	11.96	6.25	.080	20.03	.285
	3.25	716	7.75	6.11	.096	20.11	.178
	3.75	725	12.02	5.66	.069	19.47	.109
82	2.75	733	19.45	6.67	.064	22.32	.220
	3.25	775	16.27	6.43	.080	20.99	.232
	3.75	780	13.65	5.99	.088	20.18	.186
83	3.25	422	8.37	5.12	.076	16.06	.087
	3.75	464	8.61	4.79	.073	15.59	.181
	4.25	509	8.61	4.51	.058	14.98	.157
84	3.25	591	11.29	5.72	.068	18.84	.273
	3.75	598	9.33	5.09	.080	17.21	.258
	4.25	586	13.84	4.73	.067	16.01	.193
85	3.25	554	6.63	5.77	.073	18.17	.162
	3.75	589	8.25	5.46	.082	16.64	.223
	4.25	579	8.20	4.91	.079	16.35	.143
86	3.00	574	9.12	5.45	.076	17.36	.164
	3.50	595	8.43	5.21	.073	16.75	.222
	4.00	592	11.43	4.80	.073	15.84	.302
87	3.00	737	11.14	7.05	.065	22.57	.261
	3.50	784	11.43	6.55	.077	20.78	.361
	4.00	751	15.88	5.96	.072	19.95	.263
88	3.25	586	12.20	5.78	.086	18.72	.159
	3.75	599	8.94	5.30	.102	17.69	.260
	4.25	622	15.94	4.96	.077	17.42	.153
89	3.00	531	11.79	4.99	.074	17.23	.141
	3.50	608	11.57	5.13	.051	18.39	.306
	4.00	639	12.16	4.60	.058	17.00	.214
90	3.00	529	11.53	5.53	.058	17.83	.130
	3.50	566	8.86	5.16	.079	16.47	.279
	4.00	596	10.29	4.92	.062	16.93	.206

TABLE III—*Continued*

Serial no.	Twist multiplier	14/1 S-twist Strength (25 breaks) Means (g.)	14/1 S-twist Strength (25 breaks) Std. error (g.)	14/3 Z-twist Strength (25 breaks) Means (lbs.)	14/3 Z-twist Strength (25 breaks) Std. error (lbs.)	14/3/3 S-twist Strength (25 breaks) Means (lbs.)	14/3/3 S-twist Strength (25 breaks) Std. error (lbs.)
91	3.50	548	10.67	5.16	.068	17.02	.089
	4.00	570	11.57	5.00	.071	16.96	.153
	4.50	570	9.12	4.71	.056	16.42	.157
92	3.50	606	9.16	5.70	.089	19.01	.171
	4.00	600	10.51	5.28	.071	17.31	.270
	4.50	622	8.51	5.01	.071	16.88	.194
93	3.00	735	9.47	6.55	.087	21.19	.161
	3.50	740	11.82	5.91	.066	19.78	.299
	4.00	717	11.33	5.47	.081	19.06	.260
94	3.00	702	9.73	5.73	.096	19.23	.206
	3.50	690	10.92	5.52	.097	18.45	.169
	4.00	686	12.55	5.21	.096	17.15	.172
95	2.75	809	13.20	5.97	.059	22.85	.324
	3.25	839	12.00	6.98	.075	22.63	.198
	3.75	829	13.84	6.26	.082	20.87	.242
96	3.00	719	7.39	6.49	.097	21.65	.237
	3.50	731	13.37	6.17	.104	20.61	.245
	4.00	714	11.96	5.56	.070	19.31	.301
97	3.25	612	8.88	5.62	.101	18.69	.202
	3.75	663	7.37	5.39	.065	17.41	.264
	4.25	660	10.16	4.94	.072	16.30	.177
98	3.25	637	13.59	6.06	.074	19.22	.220
	3.75	661	11.18	5.62	.076	19.09	.185
	4.25	658	11.75	5.25	.071	17.63	.173
99	3.25	729	9.26	6.46	.099	21.85	.228
	3.75	725	17.06	6.14	.088	20.56	.257
	4.25	722	13.80	5.52	.084	18.57	.143
100	3.25	556	11.80	5.45	.084	18.04	.163
	3.75	599	9.78	5.21	.062	16.91	.222
	4.25	607	9.69	4.91	.054	16.63	.244
101	3.25	659	12.33	6.33	.058	20.46	.207
	3.75	618	8.57	5.43	.092	17.98	.228
	4.25	632	12.02	5.12	.077	17.44	.222
102	3.25	981	13.18	7.68	.097	26.20	.236
	3.75	958	11.02	7.38	.096	25.00	.354
	4.25	962	15.33	6.84	.076	23.69	.202
103	3.00	817	10.71	7.23	.068	24.68	.200
	3.50	888	13.94	6.80	.122	23.50	.247
	4.00	795	19.90	6.07	.092	21.25	.292
104	2.75	746	10.16	6.75	.073	23.11	.234
	3.25	807	10.41	6.75	.064	21.88	.253
	3.75	791	16.92	6.26	.082	20.59	.247
105	3.00	746	11.61	5.63	.065	20.09	.176
	3.50	752	13.90	5.50	.063	19.63	.237
	4.00	718	17.92	5.09	.077	17.82	.215

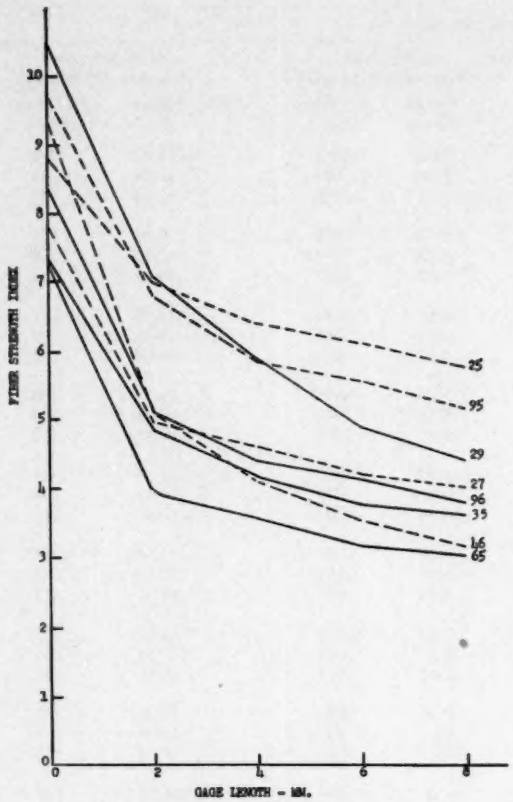

FIG. 1. *Variation of fiber strength index with gage length.*

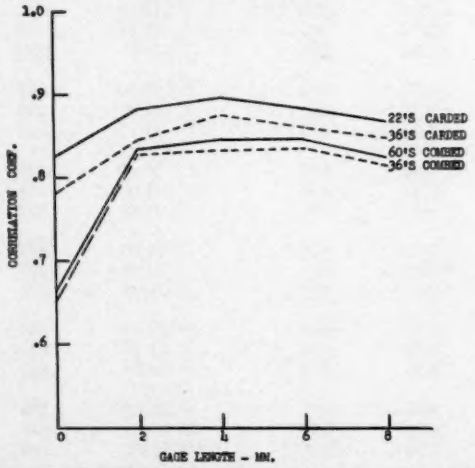

FIG. 2. *Correlation of single end yarn strength with fiber strength at different gage lengths for first 75 cottons.*

TABLE IV. AVERAGE PRESSLEY INDICES AND STANDARD ERRORS FOR ALL COTTONS TESTED AT EACH JAW SPACING

Jaw spacing mm.	Average Pressley index lb./mg.	Average standard error lb./mg.	Standard error as a percentage of Pressley index (%)
0	7.78	.088	1.13
2	4.80	.064	1.33
4	4.16	.047	1.13
6	3.80	.041	1.07
8	3.55	.034	.95

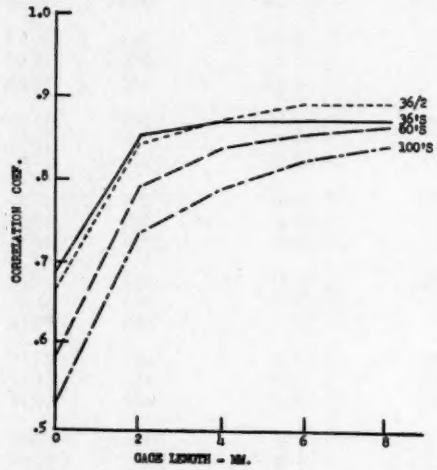

FIG. 3. *Correlation of yarn skein strength with fiber strength at different gage lengths for combed yarns.*

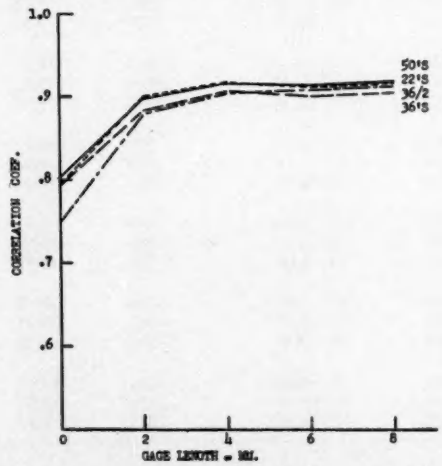

FIG. 4. *Correlation of yarn skein strength with fiber strength at different gage lengths for carded yarns.*

centages of the means they still decrease with increase in gage lengths (see Table IV).

It seems from this rather extensive study that both for single end breaks and skein breaks there is a higher correlation between fiber strength and yarn strength when the fiber is tested at longer than the so called zero lengths between 3 and 4 mm. The data shows there was a greater gain in correlation at longer gage lengths for combed yarns than for carded yarns. This was true both for single end breaks and skein breaks. For single end breaks the correlation decreases for gage lengths longer than approximately 4 mm. (see Figure 2). For carded yarns the correlation for skein strength remains approximately constant at gage lengths from 4 to 8 mm. but for combed yarn increases all the way to 8 mm. which was the maximum gage length used (see Figures 3 and 4).

For the yarns made at Clemson from the last 30 cottons the correlation was approximately constant with gage length. This was true for the 14's singles twist singles, in which case there was a decrease in correlation with increased gage length. This is strange since a decrease did not occur in the singles or in the tire cord made from the low twist multiple singles. It seems surprising that these yarns did not show increased correlation with gage length as did the 75 yarns from the U.S.D.A. laboratories.

Realizing that the yarns from the government laboratories had probably been spun with optimum twist, the correlation was computed for the 30 yarns using the highest strength obtained for each yarn from any of the three twist multiples. Again the coefficients of correlation were nearly constant for all gage lengths (see Figure 6).

There was some question whether 30 yarns was a sufficiently large number from which to compute really accurate correlation coefficients. So the count strength product was used to compute equivalent strength of 22's from the optimum strength of the 14's. These values were then used along with those for 22's yarn from first 75 cottons and new correlation coefficients were computed for all 105 cottons giving the upper curve shown on Figure 5. It is seen then that the increase in correlation with gage length is almost identical with that for the first 75 cottons.

It is interesting to note that from all the different yarn sizes tested, the increase in correlation for longer gage lengths is greater the finer the yarn, so that possibly 14's should not be expected to show the gain with gage length that was found for the higher yarn numbers. Another point to note is that in general the correlation is higher for coarser yarns than for finer yarns but more so for the shorter gage lengths, even zero gage length. Possibly the equivalent gripping distance on the fiber during the break is shorter for heavy yarn and longer for light yarns. A study of heavier yarns would be interesting.

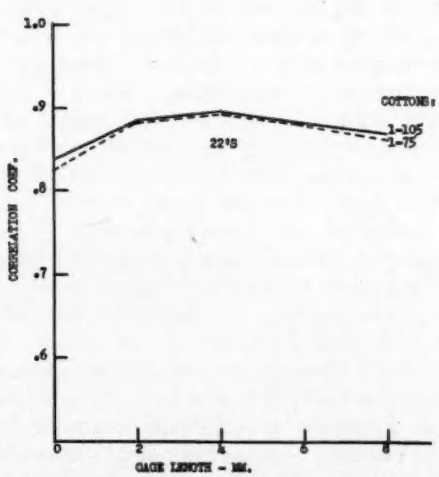

FIG. 5. *Comparison of correlation of single end yarn strength with fiber strength for first 75 cottons and all 105 cottons.*

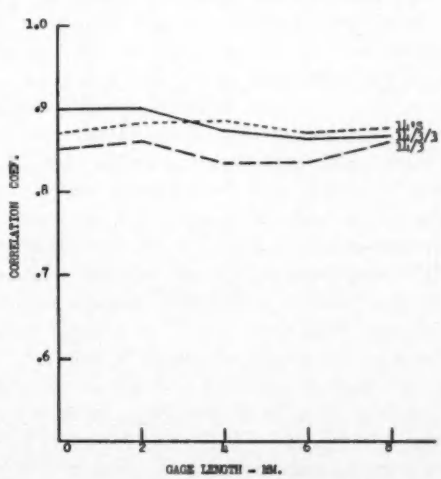

FIG. 6. *Correlation of single end yarn strength with fiber strength for the last 30 cottons.*

Conclusions

The data seems to prove that in general fiber strength measured at longer gage length will give a better indication of yarn strength than will fiber strength at so called zero gage length. In singles yarn breaks it seems that the fibers break as if the equivalent gripping distance on the fibers were approximately 3 mm.

It seems that in flat bundle measurements there is a smaller percentage error at longer gage lengths.

Possibly this sort of a study should be made on the correlation of fiber breaking strength with the breaking strength of fabrics made of the same cotton. The real value of yarns is not so much their own strength as the quality of the fabrics made from them.

Acknowledgment

The Textile School expresses appreciation for the opportunity provided by the U.S.D.A. for carrying out this interesting project. The men doing this research should be mentioned as follows: Mr. W. C. Whitton—all fiber breaks and computation of results and correlations. Mr. H. L. Loveless—preparation of flat bundle samples and computation of results and correlations. Messrs. L. H. Jameson and H. B. Wilson—single end and skein breaks and computation of results. Mr. J. L. Thompson—manufacturer of yarns made at Clemson.

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(Manuscript received September 17, 1953.)

Letters to the Editor

Short communications in the form of Letters to the Editor are intended to provide prompt publication of significant new research results and to permit an exchange of views on papers previously published in the Journal. These communications are not submitted to formal review as are research papers, and the editors do not assume any share of the author's responsibility for the information given or the opinions expressed. When work previously published in the Journal is the subject of critical comment, the authors of the original paper are given an opportunity to submit a reply, which will be published concurrently when possible.

Diffusion-Controlled Sorption of Water by Wool Fibers

Commonwealth Scientific and Industrial Research Organization
Division of Animal Health and Production
Prospect, Australia
December 4, 1953

To the Editor
Textile Research Journal

Dear Sir:

No reports appear to be available of the rate at which the regain of a wool fiber comes into equilibrium with the atmosphere at its surface when diffusion is the only rate controlling process. This is probably largely due to the difficulty that the regain of a fiber is very dependent on temperature as well as humidity, and that in most circumstances a change in regain is accompanied by considerable, and often inaccurately measurable, changes in the temperature of the fiber and in the temperature and humidity of the atmosphere at the fiber surface.

Regain *vs.* time curves have been obtained at a number of fixed temperatures and humidities by measuring the regain changes which occur in air streams which are so rapid that the temperature of the fiber, and the temperature and humidity of the air at the fiber surface, differ negligibly from the temperature and humidity of the main air stream. The accuracy of this statement for the conditions of the measurements reported here, namely, a linear air velocity of 11.5 ft./sec., has been established both by calculations based on measurements made in a parallel investigation of heat transfer constants for air flowing through fibrous masses, and by measuring the regain changes that occur with air velocities ranging from 0.3 ft./sec., to 15 ft./sec. The change in regain did not increase with increase in velocity above about 3.5 ft./sec.

The measurement procedure was as follows: About 0.1 g. of cleaned wool was spread into an even web over a 2-in. diameter hole in a frame of aluminum $2\frac{1}{4}$-in. × $2\frac{3}{8}$-in. × $\frac{1}{32}$-in., and bound in place in a mesh of 0.006-in. Advance wire. After conditioning to the required equilibrium regain the frame and wool were sealed in a small envelope of silver foil and weighed. The frame was then withdrawn from the envelope and placed over an orifice through which air of the required temperature and humidity flowed at 11.5 ft./sec. At the end of the required exposure time the frame was sealed in another envelope held immediately under the orifice and reweighed. Regain changes of about 0.5% occurring during the interval between opening the envelope and locating over the orifice have been determined and allowed for.

The curves in Figure 1 indicate the progress with time of the adsorption and desorption processes under various conditions. The diameter of the fibers used was 24μ, except for curve *C* for which the diameter was 36μ. Curve *A* shows that when fibers which are initially dry absorb water at 25°C from an atmosphere of 82% R.H. half the equilibrium regain is attained in 20 sec., and three quarters in 40 sec. Curve *D* shows the desorption process for the reverse condition—*i.e.*, a fiber initially in equilibrium with an atmosphere of 82% R.H. desorbing at 25°C in dry air (1% R.H.). It will be seen that desorption starts at a faster rate than absorption but then becomes much slower. The time for half the change to equilibrium regain thus becomes the same

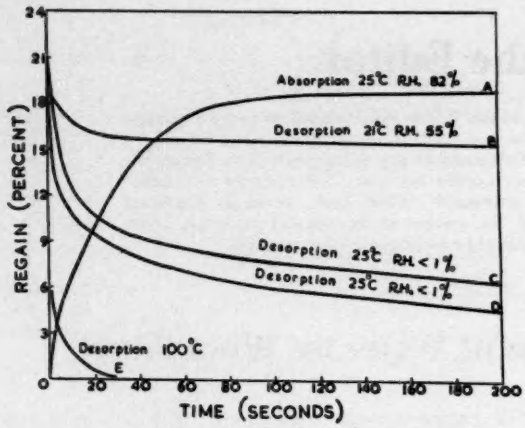

FIG. 1. *Regain* vs. *time curves, for various conditions. For curve* E *the initial regain was 20.4%.*

as for absorption, but the time for three quarters of the change is 190 sec. instead of 40 sec. The increase in the rate of desorption with increase in temperature is indicated by curve *E*, where it is seen that at 100°C the time for three quarters of the regain change is reduced to about 2 sec. Increasing the diameter of the fibers decreases the rate as indicated by curve *C*, which is for fibers of 36μ. The time to the three quarter point is now off the graph at 270 sec. in comparison with 190 sec. for the 24μ fibers of curve *D*. Curve *B* shows the desorption at 25°C from an equilibrium regain of 19% to an equilibrium of about 14.5%. The time to the three quarter point appears to be not more than 50 sec. showing that equilibrium is attained more rapidly at high than at low regains.

The regain changes take several times as long as would be expected [1] from the most relevant previous evidence—*viz.*, King's data [2] on the diffusion of water in horn keratin. Whether the difference between the results for horn and wool are attributable to differences in chemical composition and structure, or to the exclusion of air in King's experiments, is being investigated. No difference was found between the rates of absorption by fresh raw wool cleaned in various cold solvents, and by wool from commercial tops.

It is hoped to publish in the near future a fuller account of the experimental work, and some calculations of the coefficients of diffusion of water in wool fibers.

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N. F. ROBERTS
A. R. HALY

The Theory of Soil-Fiber Complex Formation and Stability

Institute of Textile Technology
Charlottesville, Virginia
December 22, 1953

To the Editor
Textile Research Journal

Dear Sir:

The able and interesting paper of Fong and Lundgren [4] has been called to our attention. These authors state that, "Compton and Hart [1] concluded . . . that the main mechanism of soil deposition is mechanical occlusion of the soil in the interstices of the fiber and between fibers, and that adsorption due to electrostatic or van der Waals' forces is relatively unimportant." This statement might be interpreted in a manner which is not in accord with our complete published work upon this subject. To avoid misunderstanding, we would like to present an integrated statement of the theories which have resulted from our work during the past four years [1, 2, 3, 5, 6, 7].

To begin with, we emphatically agree with Fong and Lundgren that, "The ability of a detergent system to prevent soil from redepositing on the fabric after it has once been removed is of equal importance to its ability to remove soil initially." As we have stated [5], "In attempting to elucidate the mechanisms of primary soil deposition and retention on fiber surfaces, two fundamental questions arise concerning the formation and stability of the soil-fiber complex, namely:

(*1.*) What is the nature of the process by which the soil-fiber complex is formed, or what are the main factors governing rate and probability of formation?

(*2.*) What is the nature of the bond between soil particles and the fiber surface, or what are the factors controlling the stability of the soil-fiber complex?

It is emphasized that the factors governing the formation of the soil-fiber complex need not be identical with those influencing the stability."

It will be seen that this is a detailed and explicit statement of the two classes of phenomena which Fong and Lundgren differentiate in their opening sentence.

Let us first consider the question of the formation of a soil-fiber or soil-fabric complex. This will depend upon the method of transmission of the soil which may be by solid borne contact or transmission via some fluid vehicle, either gaseous or liquid. For the sake of simplicity, we shall restrict the argument to the case most commonly studied, namely, that of liquid borne solid soil in a system in which the fabric is totally or partially immersed in the soil-carrying liquid vehicle. Such systems are those in which "soil redeposition" occurs.

If a given fabric is exposed to a soil-bearing liquid by a procedure such as that of Fong and Lundgren, or as occurs in laundering and dry cleaning, then at the start of the drying process, the soil present in the system may be divided in two classes [2]: (*1*) soil suspended in the bath liquor adherent to or interpenetrating the fabric; and (*2*) soil attached to the fiber surfaces.

The amount of the first class of soil present is dependent on diffusion and flow phenomena, and will be affected only slightly, if at all, by coulombic or other surface forces. An exception to this may be the penetration of the finer capillaries of the fabric structure by soil particles, in which case it is possible that electrostatic fields of similar sign on the fibers and soil particles may prevent or greatly reduce such diffusion. Solvation or other adsorption phenomena which *increase* the effective radius of the particle and *decrease* the effective radius of the fine capillaries might give rise to similar action.

We may now consider soil of the second class, namely, that attached to the fiber surface. Two factors govern the formation of the soil-fiber complex prior to drying [5]—*i.e.*, (*1*) probability of close approach by the soil particle to the fiber surface; and (*2*) probability of interaction of the soil particle with a suitable acceptor site on the fiber surface.

It may seem tautologic to say that the soil-fiber complex cannot be formed without close approach of the soil particle to the fiber surface, but this point must be emphasized, as it is during this process that the variables of solvation, wall charge, surfactant adsorption, protective colloid action, *etc.*, play a major role.

As regards the probability of interaction of a soil

particle with a fiber substrate, it will be affected not only by the factors which we have just mentioned, but by the nature of the bond which is formed. There are three, and only three ways that a fabric can retain soil; or to phrase it differently, there are only three possible binding mechanisms for a soil-fabric complex [1]. These are: (*1*) macro-occlusion, or entrapment of particles in the intrayarn and interyarn spaces [7]; (*2*) micro-occlusion, or entrapment of particles in the irregularities of the fiber surfaces; and (*3*) sorptive bonding of the soil to the fiber by van der Waals' or coulombic forces. This will, in general, require the establishment of an interface between the fiber and a reasonable portion of the surface of the soil particle.

The first of these mechanisms covers the case of the first class of soil described above. Direct attachment of the soil to the fiber substrate must be by one of the last two mechanisms.

The type of bond which is formed in the primary stage of deposition depends upon the phase states of the soil and the fiber substrate. It is known that the formation of an interface between two phases occurs only by deformation of the surface of one or both phases, as in pressure welding and wetting, or by the accretional build-up of one phase, as in electrodeposition, crystallization, or adsorption. If, therefore, both soil and fiber are rigid and nondeformable under the conditions of treatment, the bond between them will be predominantly micro-occlusive. As the deformability of either soil or fiber increases, the probability of formation of a sorptive, or interfacial bond, will increase [3].

We may turn now to the question of the stability of the soil-fabric complex, which is the basic problem of detergency. This will depend upon the nature of the bonding mechanism, or mechanisms, which are operative [3]. It is not difficult to see that, while detergents may be of major importance as regards a sorptive or interfacial bond, they could have little effect on a geometric one. As both types of bonds are present in nearly all real systems, it is not surprising that the evaluation of detergent action has been so difficult and lacking in reproducibility.

In this connection, we should like to mention a little understood but extremely important process, *to wit*, that of drying. We have called this [1] "secondary deposition," and we have found, as was already well known, that if a system consisting of fabric or fibers with a soil dispersion is dried, the amount of soil retained by the fabric or fiber substrate is enormously increased, as is the tenacity with which such soil is held. As we have already excluded the possibility of any modes of soil binding except those given, it can only follow that the process of drying greatly increases binding of soil to fiber by one or more of the modes which we have described.

It is known that collapsing films can exert great pressures. If we consider a single fiber surrounded by a film of liquid in which soil particles are dispersed, it is evident that as evaporation takes place, the cylinder of liquid will contract until the distance between the fiber surface and the liquid becomes the same as the diameter of some given particle. At this point, the pressure upon this particle ceases to be hydrostatic and becomes unidirectional, causing pressures to develop between the soil particle and the fiber substrate or underlying particles. These pressures may reach magnitudes which cause deformation of particle and/or fiber surface as well as rapid interchange of particles by the same mechanisms, and hence form the agglomerates on a fiber substrate which may be observed under a microscope.

There is a tremendous range of real systems in which soiling and detergency may occur. For either process, the final state arises from the subtle and intricate interplay of a group of variables. While we have pointed out the importance of a hitherto neglected factor in soiling and detergency, namely, micro-occlusion, we do not wish to be understood as considering this the only important factor in this field of study.

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JACK COMPTON
W. J. HART

The Relationship Between Micronaire-Fineness and Causticaire-Maturity for Various Cotton Samples

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AND STOOMSPINNERIJ TE NIJVERDAL N.V.
Technological Laboratory
Nijverdal, Holland
October 30, 1953

To the Editor
TEXTILE RESEARCH JOURNAL

Dear Sir:

The Causticaire-method for determining cotton maturity [1] has been used in our laboratory for almost a year now. In our opinion it is a good practical method, which can be carried out along with the normal routine fiber testing.

There arise, however, some questions when plotting the Causticaire-maturity index against the Micronaire-fineness of the untreated sample. In Figure 1 this is carried out for about 200 cotton samples of various origin—*viz.*, American Upland, Mexican, Central American, Peruvian, Argentine, Egyptian, Uganda, Sudan, Iranian, and Turkish cottons.

In all these cases we find a high correlation between maturity index and fiber fineness, independent of the type of cotton. Assuming the maturity value of 76% as the limit between average maturity and immaturity [2], we may conclude from this graph that all cottons with a Micronaire-fineness < 3.5 will be immature and all cottons with a fineness > 4.0 will be mature. Cottons with a fineness between these two values can be mature or immature.

The parabolical shape of this curve is obtained when using the curvilinear Micronaire scale; plotting the linear scale gives a linear relationship (Figure 2).

When calculating the Causticaire-fineness according to [3] with the aid of the formula

$$\text{Causticaire-fineness} = 1.185 + 0.00075\ T^2 - 0.020\ MI,$$

where T = average of Causticaire readings on treated specimen and MI = maturity index, and plotting Micronaire-fineness M against Causticaire-fineness C for the same 200 samples, we obtain the diagram of Figure 3. All cottons with a $MI < 76$ (o) are located at the left side of the line $C = 2.20\ M - 4.34$ and all cottons with a $MI > 76$ (●) at the right side of this line.

The following questions arise:

(*1.*) Is the Micronaire-fineness indeed independent of origin, variety, growth, soil, irrigation, etc., of the cotton?

(*2.*) Is the Micronaire-fineness defined by fiber

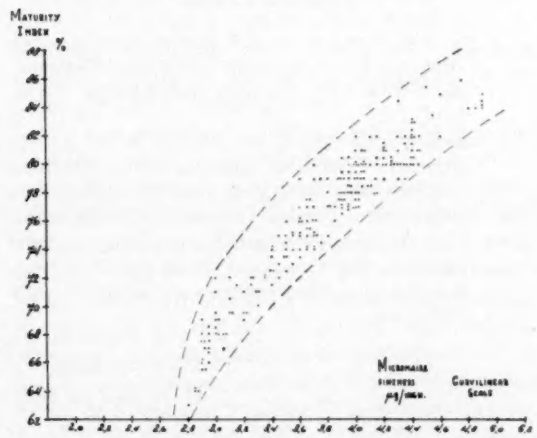

FIG. 1. *Micronaire-fineness (curvilinear scale) plotted against maturity index.*

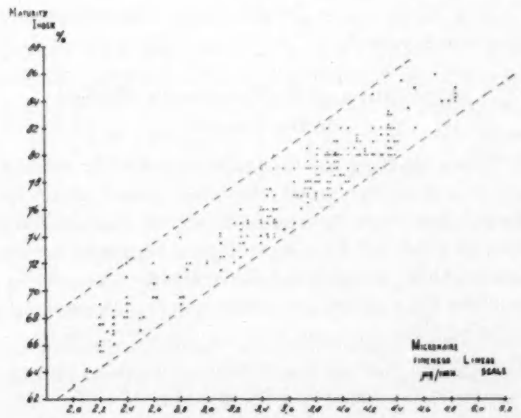

FIG. 2. *Micronaire-fineness (linear scale) plotted against maturity index.*

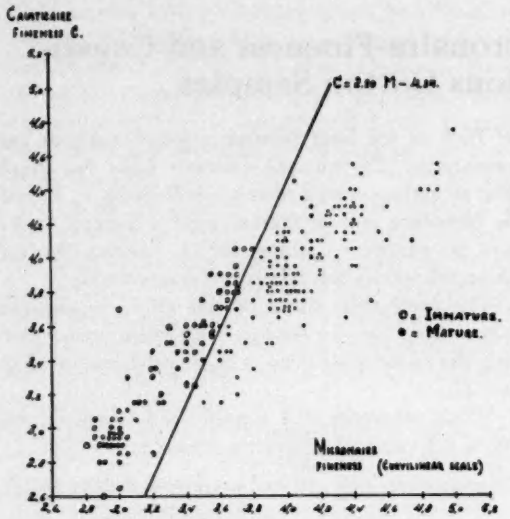

FIG. 3. *Micronaire-fineness (curvilinear scale) plotted against Causticaire-fineness.*

growth only? If so, it will only be necessary to make a determination of fiber-maturity for cottons with a Micronaire-fineness (curvilinear scale) between 3.5 and 4.0 μg./in.

(*3.*) Does the tentative maturity limit of 76% perhaps not apply for all cottons, especially in respect to the influence of maturity on the spinning and dyeing properties of the fiber?

(*4.*) It is a well-known fact that certain finer cottons are highly appreciated in the cotton trade; could it be that all these cottons are more or less immature?

(*5.*) What can be the meaning of the relationship found in Figure 3?

Application of the Causticaire Method on the Comber

When applying the Causticaire method on comber sliver and comber waste, the latter turned out to be much finer than the sliver, as shown for a certain case in Table I. The same relation between fineness and maturity as described above applies here.

From this fact we can conclude the following:

(*1*) The comber not only eliminates the shorter, but also the finer and more immature material (within one sample, fiber length, fiber fineness, and fiber maturity will be more or less correlated).

TABLE I

	Sliver	Waste
Micronaire-fineness (μg./in.) (curvilinear scale)	4.25	3.25
Causticaire-maturity index (%)	82.5	72.0

(*2*) The methods for attaining a fiber diagram which are based on the calculation of the number of fibers within a certain length group by dividing the weight of this group by its mean fiber length—*e.g.*, as is the case on apparatus of the type Johannsen-Zweigle—are not right. These methods assume the same specific weight of the fiber in all fiber length groups, which is obviously not the case.

We would appreciate comment on this subject and hope that this letter may give rise to some elucidating reactions.

Acknowledgment

We wish to thank the Directors of Koninklijke Stoomweverij te Nijverdal N.V. and Stoomspinnerij te Nijverdal N.V. for their kind permission to publish these results and Mr. Alberts of the Fibre Research Institute T.N.O. for some interesting discussions on this subject, especially on the use of the linear Micronaire scale.

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INDUSTRIAL SECTION

Effect of Single and Ply Twists on the Properties of a 31/2 Carded Cotton Yarn

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Abstract

The effect of single and ply twists on the properties of a 31/2 cotton carded yarn was studied. A widely grown cotton variety (Deltapine) of average fiber properties was spun into a 31/1 yarn (Z twist) using a range of twist multipliers (2.9–6.9). Each single yarn twist multiplier construction was then 2-ply twisted (S twist) with a range of twist multipliers (1.9–7.9). Maximum ply strength was obtained when low-twist single yarns were 2-ply twisted with a high twist multiplier. Maximum elongation at break was obtained with a similar single-ply twist construction. For certain twist constructions single and ply twist may be varied within reasonable limits without materially decreasing strength. When the same twist multiplier was used in the single and ply yarn, maximum ply yarn strength was realized with that twist multiplier which resulted in maximum single yarn strength. Elongation is related linearly and directly to equivalent twist multiplier constructions. The ratio of ply to single yarn strength, based on maximum ply yarn strength, was highest when single yarn strength was lowest (low twist), decreased rapidly as the single yarn strength approached maximum, became approximately constant in twist combinations resulting in single yarns of maximum strength, and increased slightly as single yarn strength decreased (very high twist).

Introduction

The twisting of cotton yarns into 2-ply construction is a basic operation in the manufacture of many standard fabrics. The properties of the component yarns of these fabrics are at best a compromise of strength, elongation, and aesthetic or appearance qualities, mainly because of the complexity of the single-ply yarn twist relationship.

Ply yarn twists are usually specified by the customer [2]; and, therefore, mills must usually resort to varying the single yarn twist in an effort to obtain maximum processing efficiency. The effect that changes in single yarn twist have on ply yarn properties is somewhat obscure. Few research studies have been reported, and the literature on the subject is rather limited in scope. Austin [3] reported that maximum ply yarn strength was obtained with a low single and a high ply yarn twist multiplier construction. In a study of "balanced" 2-ply carded cotton yarns within a narrow twist range, Zobel [5] found that "the strength ratio of balanced 2-ply yarns to the single yarns from which they were produced is constant regardless of yarn size, and increases uniformly with increases in residual single yarn twist and balancing yarn twist; but the rate of increase is greater for coarser yarns." Kershaw [4], investigating wool yarn numbers using a limited range of twists, found that changes in single yarn twist resulted in increases in strength for coarse yarns, and insignificant changes in strength for medium and fine yarns.

In view of the limited information available on the effect of single and ply yarn twists on ply yarn properties, and the necessity of having this type of information to pursue a study relating fiber strength to ply yarn properties, the Southern Regional Research Laboratory initiated a study of broad scope in this field. It is to include a practical range of yarn numbers and twists for single and ply yarns. This first report is based on one type of cotton and one

* One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

yarn number of varying single and ply twists. Other work in progress has shown that the length and fineness of the cotton fibers and the yarn number influence these relationships. Therefore, these findings are only applicable for cottons which have the same general fiber properties and for the yarn number used in this study.

Procedures and Methods

Using the Whitin Casablanca * long-draft spinning frame ($3\frac{1}{2}$ in. gage), one yarn number (31/1) was spun (Z twist) from a widely grown cotton variety (Deltapine) of average fiber properties: classer's staple length $1\frac{1}{16}$ in.; Fibrograph upper-half mean length 1.09, mean length 0.86, uniformity ratio 79; Micronaire fineness 4.3; Pressley strength index 7.4; and maturity 82%. Twist multipliers (T.M.) for the single yarns ranged from 2.9 to 6.9 in increments of 1.0. Each single yarn twist multiplier construction was 2-ply twisted (S twist) on a Whitin twister ($4\frac{1}{2}$ in. gage) with twist multipliers ranging from 1.9 through 7.9, also in increments of 1.0. Single yarn number was held constant by varying the spinning draft to compensate for the contraction due to increases in twist.

All tests and test conditions were in accordance with A.S.T.M. procedures [1]. Skein strength determinations were made on a pendulum type tester, and single strand and elongation determinations on an inclined-plane type tester. The former determinations were made on all constructions, whereas the latter were made on all single yarn constructions, but only on the ply yarns using 1.9, 3.9, 5.9, and 7.9 ply twist multipliers.

* Mention of trade names does not imply their endorsement by the Department of Agriculture over similar products not mentioned.

Analysis of Data

The strength and elongation of ply yarns were analyzed from five standpoints: (*1*) varying ply yarn twist while holding single yarn twist constant; (*2*) varying single yarn twist while holding ply yarn twist constant; (*3*) equivalent single and ply yarn twist multiplier combinations; (*4*) ply-single yarn strength ratios; and (*5*) variation in strength values.

Effect of Ply Yarn Twists

Strength Data

Figure 1 shows curves which relate ply yarn twist to skein strength when the twist in the single yarn is held constant. Maximum strength values increase as the single twist decreases, but at successively higher ply yarn twists. Maximum ply yarn strength was obtained with a 2.9 single and a 6.4 (approximately) ply twist multiplier combination.

Changes in ply yarn twist result in more rapid changes in strength up to maximum for the low-twist (2.9 T.M.) single than for the high-twist single yarns (6.9 T.M.). Beyond maximum strength, however, and with increasing ply twist, ply yarn strengths decrease at about the same rate irrespective of single yarn twist. The maximum strength plateau of each curve indicates that changes in ply yarn twist (about one twist multiplier) do not cause significant changes in ply yarn strength.

There is an area of approximate coincidence of skein strengths for constructions made from single yarns spun with 2.9–4.9 twist multipliers and plied with 3.9–4.4 twist multipliers.

Figure 2 shows curves which relate ply yarn twists to single strand strength when the twist in the

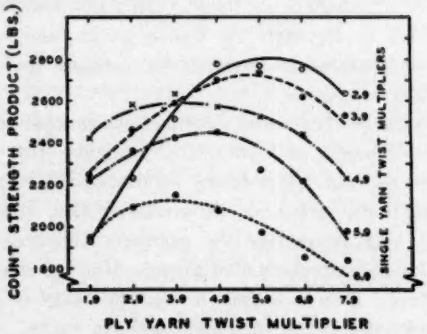

FIG. 1. *Effect of ply twist on skein strength of a 31/2 carded cotton yarn.*

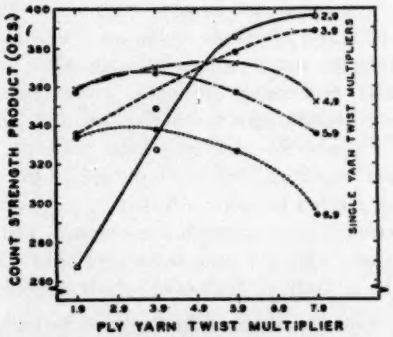

FIG. 2. *Effect of ply twist on single strand strength of a 31/2 carded cotton yarn.*

single yarn is held constant. Generally, these curves resemble those based on skein strength values (Figure 1) and lead to somewhat similar conclusions. However, maximum single strand strengths were obtained with higher ply yarn twists for low single twist multipliers and with lower ply yarn twists for high single twist multipliers. This diverging shift for points of maximum strength at single twist multiplier extremes is reflected in more elongated plateaus for the medium and high single twist multipliers (4.9, 5.9, and 6.9) than occur with curves based on skein strength values. The maximum ply yarn strength for all twist combinations used was obtained with a 2.9 single-7.9 ply twist multiplier construction. Two curves (2.9, 3.9) reached, but did not exceed, points of maximum strength, maintaining a direct relationship with ply twist; whereas the three high single twist multiplier curves (4.9, 5.9, and 6.9) did exceed points of maximum strength.

An area of approximate coincidence of single strand strengths similar to that noted for skein strengths (Figure 1) was found for constructions using ply twist multipliers of 4.4–5.4 in combination with single twist multipliers of 2.9–5.9.

Elongation Data

Figure 3 shows curves which relate ply yarn twist to elongation at break, when twist in the single yarn is held constant. Generally, ply twist and elongation are positively correlated—*i.e.*, increases in the former produce increases in the latter, regardless of the amount of twist used in the single yarn. Maximum ply yarn elongation is obtained with a low single (2.9) in combination with a high ply (7.9) twist multiplier. As single yarn twist multipliers are increased from 2.9 to 6.9, the effect of ply yarn twist on elongation becomes progressively less important. In fact, with the higher single twist multipliers (5.9 and 6.9) changes in ply twist from 1.9 to 4.9 cause insignificant changes in elongation. Single yarn twist is a more important factor of elongation with low than with high ply twist, as shown by the convergence of the elongation curves as ply twist is increased.

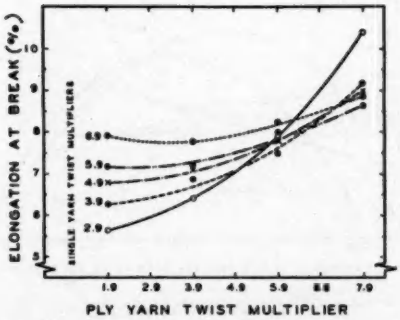

FIG. 3. *Effect of ply twist on elongation of a 31/2 carded cotton yarn.*

Effect of Single Yarn Twist

Strength Data

Figure 4 shows curves which relate single yarn twist to ply skein strength when ply twist is held constant. Increases in single yarn twist from 2.9 to 4.9 twist multiplier result in significant increases in ply skein strength for 1.9 and 2.9 ply twist multiplier constructions, in little or no increase in ply skein strength for the 3.9 ply twist multiplier construction, and in decreases in ply skein strength for 4.9, 5.9, and 6.9 ply twist multiplier constructions. Increases in single yarn twist multipliers from 4.9 to 6.9

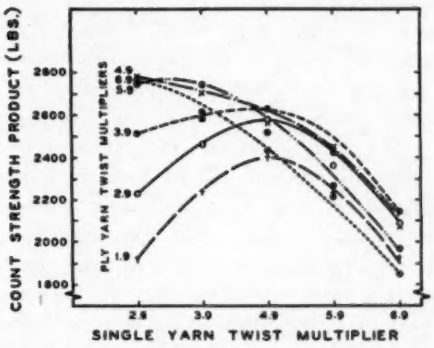

FIG. 4. *Effect of single yarn twist on skein strength of a 31/2 carded cotton yarn.*

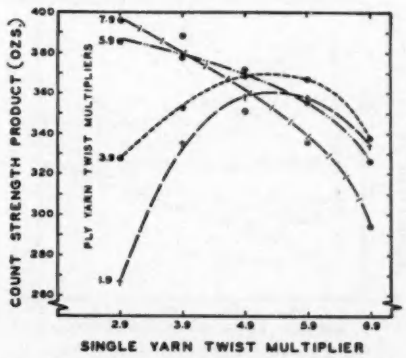

FIG. 5. *Effect of single yarn twist on single strand strength of a 31/2 carded cotton yarn.*

resulted in approximately equal rates of decrease in ply skein strength for all ply twist constructions. Maximum strength plateaus, when compared with those in Figure 1, are almost nonexistent.

Figure 5 shows curves which relate single yarn twist to single strand strength when ply twist is held constant. These curves are similar in character to those based on skein strength values (Figure 4) and lead to practically the same conclusions. However, for yarns plied with 1.9 and 3.9 twist multipliers, higher single yarn twist multipliers were required to obtain maximum single strand strength than were required for maximum skein strength.

Elongation Data

Figure 6 shows curves which relate single yarn twist to elongation at break when ply twist is held constant. Elongation and single yarn twist are directly related for ply yarns twisted with 1.9 and 3.9 twist multipliers—that is, elongation increases with increases in single yarn twist. There is no appreciable difference in elongation over the whole range of single yarn twist multipliers when ply yarn is twisted with a 5.9 twist multiplier. In yarn plied with a 7.9 twist multiplier, elongation and single yarn twist are inversely related up to 5.9 (approximately) single yarn twist multiplier, after which further increases in single twist have little effect.

The converging characteristics of these curves, as single yarn twist multipliers increase, demonstrate that elongation, regardless of ply twist, is influenced more by low than by high single yarn twists.

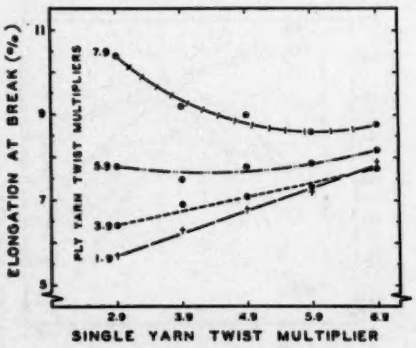

FIG. 6. *Effect of single yarn twist on elongation of a 31/2 carded cotton yarn.*

Equivalent Single and Ply Yarn Twist Multipliers

Strength and Elongation Data

Figure 7 shows curves for skein and single strand strength and elongation values for equivalent single and ply yarn twist multipliers. Maximum skein strength was obtained with approximately a 4.4/4.4 combination of single and ply twist multipliers, and maximum single strand strength with a 5.2/5.2 combination. Each strength curve has a plateau where changes in equivalent twist combinations (about one twist multiplier) cause insignificant changes in strength. Elongation is related linearly and directly to equivalent twist multiplier constructions.

Ply-Single Yarn Strength Ratios

To determine the gains in strength (skein and single strand) of ply over single yarns, ratios of the ply yarn count-strength products to single yarn count-strength products were calculated. The values plotted are based on (*1*) the ply twist multiplier resulting in maximum ply yarn strength and (*2*) the equivalent twist multiplier constructions.

In Figure 8, the highest maximum ply yarn strength ratio (1.74) was obtained with a 2.9 single and a 6.4 ply twist multiplier construction. These ratios decrease rapidly with increasing single yarn twist up to the twist multiplier (4.4 approximately) required for maximum single yarn strength. With increasing single yarn twist, the ratios increase slightly to approximately 1.20.

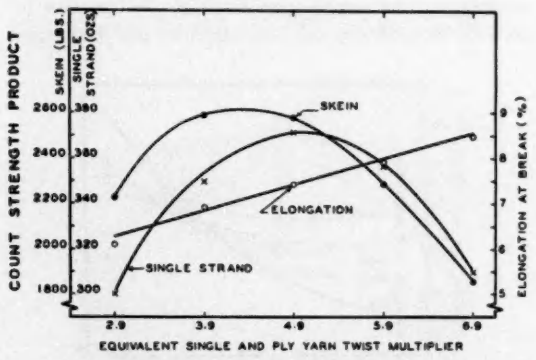

FIG. 7. *Effect of equivalent single and ply twist multiplier on skein and single strand strength and elongation of a 31/2 carded cotton yarn.*

In Figure 9 the highest single strand strength ratio (1.66) was obtained with a 2.9 single and a 7.9 ply twist multiplier construction. These ratios decrease rapidly with increasing single yarn twist up to the twist multiplier (4.9 approximately) required for maximum single yarn strength. In combinations using single yarn twists higher than those resulting in maximum yarn strength, the ratios increased gradually to approximately 1.40.

The ratios of ply to single yarn skein strength based on equivalent single-ply yarn twist multiplier combinations (Figure 8) have a maximum value (1.39) with the 2.9/2.9 twist multiplier combination. Relatively speaking, these ratios are lower in value than those based on maximum ply yarn skein strength.

The ratios of ply to single yarn single strand strength based on equivalent single-ply twist multiplier combinations (Figure 9) have a maximum ratio (1.40) with the 6.9/6.9 twist multiplier combination. At the lower twist multiplier construction these ratios are much lower than those based on maximum ply yarn single strand strength; but with the 4.4/4.4 (approximately) twist multiplier combination and above, these two ratio curves practically coincide.

Variation in Strength Values

Ply yarn variability, evaluated in terms of coefficients of variation based on single strand strength observations, increased gradually, but consistently, as single yarn twist increased for all ply twist constructions. When skein strength values were similarly evaluated, however, this trend was less pronounced.

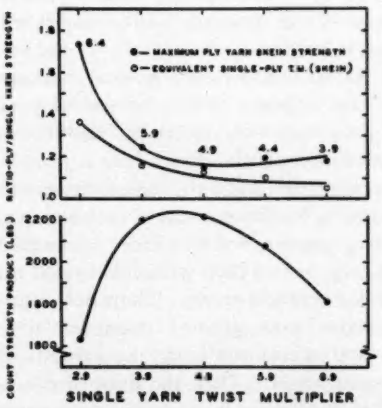

FIG. 8. *Skein count strength products of a 31/1 and ratios of 31/2 to 31/1 carded cotton yarns.*

Practical Considerations

These findings show that strength, elongation, and, indirectly, aesthetic properties of ply yarns must be compromised, since it is impossible to obtain maximum values for each simultaneously. These data provide a basis for producers of 2-ply yarns to select single-ply yarn twist multiplier combinations which will produce yarns of required quality at maximum processing efficiency.

Since balanced, equivalent, or closely related constructions are generally associated with 2-ply processing, spinners probably cannot obtain maximum strength because these constructions retain Z twist in the single yarns, whereas maximum strength is obtained only after the twist in the single yarns has been reduced to zero or even reversed, being effectively S on S twist. This condition (S on S twist), while producing 2-ply yarns of high strength, could be undesirable from the standpoint of physical characteristics, such as kinkiness, which would probably present handling difficulties in subsequent processes, or restrict its suitability for some end-uses.

On the other hand, the study shows that for popular constructions both single and ply twist may be varied within reasonable limits without materially decreasing strength. This condition permits a certain flexibility in spinning and twisting organizations which can aid processors to meet production or other end-use requirements advantageously.

Producers of 2-ply yarns who spin their single yarns in the area of maximum strength and who use equivalent twist multiplier constructions will obtain maximum strength in their ply yarns.

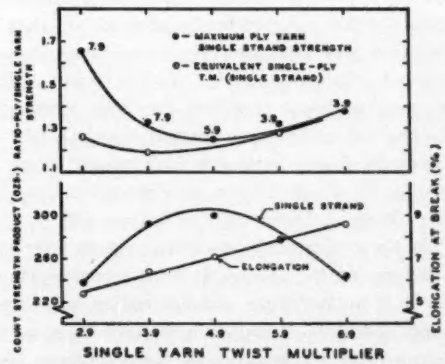

FIG. 9. *Single strand count strength products and elongation of a 31/1 yarn and strength ratios of 31/2 to 31/1 carded cotton yarns.*

It should be recognized that, while the evaluation of the data from the two test methods (skein and single strand) shows the same general trends, the single-ply twist combinations required to produce ply yarns of maximum strength are not coincident. Therefore, this report presents an opportunity to spinners to make their own evaluation of results on the basis of the test method used by them.

Acknowledgment

The authors wish to express sincere thanks and gratitude to fellow staff members of the Cotton Mechanical Processing Division for processing the cotton into yarns and making the calculations and charts, and to the members of the Testing Section of the Analytical and Physical Division for making physical tests on the yarns.

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(Manuscript received October 15, 1953.)

Ultraviolet Screening Properties of Certain Pigment Vehicle Combinations

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THE LATEST DEVELOPMENTS in the evolution of chemical finishing of cotton fabrics offer much promise to cotton in its competition with synthetic fibers for the textile market. These relatively recent developments employ "chemical modification" whereby cotton is chemically treated so that the composition and structure of the cellulose molecule are altered without destroying the fiber form. These newer approaches to chemical finishing, exemplified by the partial acetylation process developed by the Southern Regional Research Laboratory, were described by Dr. C. H. Fisher, its Director, at the 1952 Cotton Chemical Finishing Conference [6].

While these chemically modified cottons offer great possibilities for the future, it may be interesting to review the performance characteristics of some of the older, additive finishes which have been used in the past to alter and enhance the functional properties of cotton fabrics. These additive finishes, although using various chemical compounds, do not react chemically with the underlying cotton of the finished fabric.

This, then, is intended to be a review of some properties of one type of additive finish which has been and is being used extensively for the production of fire, water, weather, and mildew resistant cotton duck. The property chosen for special emphasis is that of the sunlight or ultraviolet resistance imparted to cotton duck by such a finish [3].

Essentially, this additive finish consists of chlorinated paraffin, antimony oxide, calcium carbonate, inorganic pigments, and fungicides. The chlorinated paraffin may be modified with chlorinated rubber or other water resistant resins. The whole composition, which is similar in physical appearance to paint, is ground and mixed with organic solvents in paint making equipment. Then the finished compound is applied to the fabric in a single step process with

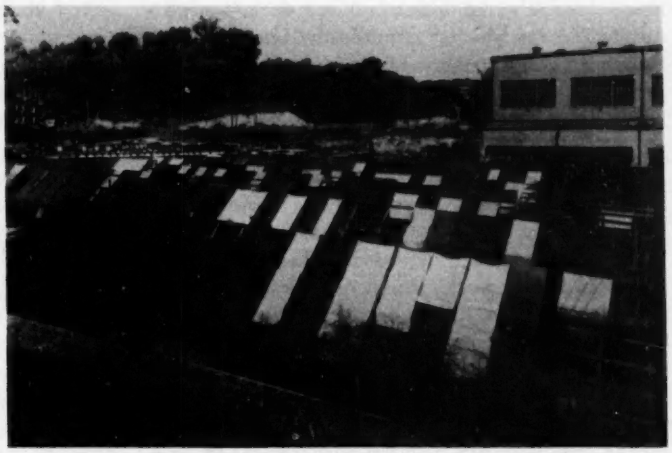

FIG. 1. *Outdoor exposure racks located at Wm. E. Hooper & Sons Co., Baltimore, Md.*

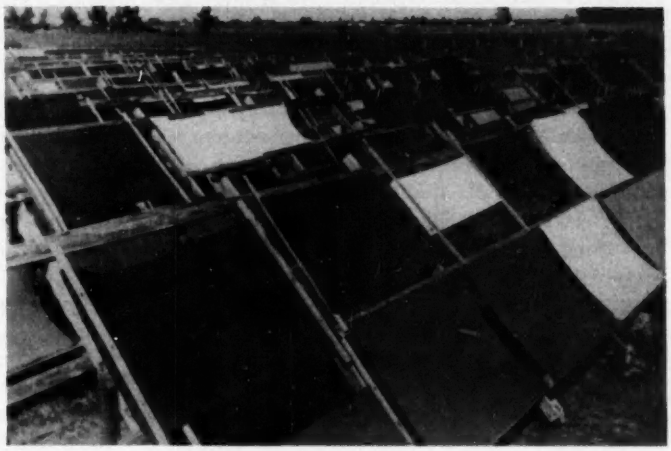

FIG. 2. *Outdoor exposure racks located in Miami, Fla.*

conventional textile finishing equipment resulting in a weight increase of the untreated fabric of from 40% to 50%.

Large quantities of cotton are used in the form of duck in the manufacture of tents, paulins, awnings, etc. The term "duck" is said to have originated from a stencil picturing a duck which was applied to heavy weight sail fabrics, made principally from Russian flax and imported to this country from England and Scotland in the early part of the nineteenth century [7]. Since that time heavy weight cotton canvas used for sails as well as other purposes has been named "duck." For this discussion two weights of duck will be considered, 10-oz., representing a type used by the Army for tents, and no. 6, representing a heavier type used for covers, paulins, etc. These square-weave fabrics are defined in Federal Specification CCC-D-771b for: "Duck, Cotton, Plied yarns (Army numbered & Tent-duck)" [5].

The minimum requirements for 10-oz. Army duck, according to this specification, are: 12.29 oz./sq. yd., 3-ply warp, 2-ply filling, 44 yarns/in. in the warp, 34 yarns/in. in the filling, and a breaking strength by the grab method of 210 lbs. in the warp, 130 lbs. in the filling. It is usually made of 13's yarn—*i.e.*, that measuring 10,920 yds./lb. The minimum requirements for the no. 6 hard texture duck are: 20.74 oz./sq. yd., 3-ply warp and filling, a count of 35 warp and 25 filling threads per in., and a minimum breaking strength of 335 lbs. in the warp and 250 lbs. in the filling direction. No. 7 yarn or that which measures 5880 yds./lb. is frequently used for the no. 6 duck.

During World War II, the U. S. Army Quarter-

master procured 1½ billion yds. of duck, approximately 75% of which was fabricated into tents [9]. A large portion of this tentage fabric was procured under the requirements of Quartermaster Tentative Specification J.Q.D. No. 242 for: Duck, Cotton; Fire, Water, and Weather resistant [12].

The data and observations for this discussion were obtained from fabrics treated for the Army by the Wm. E. Hooper & Sons Co., under the trade name "Fire Chief" during the years 1940–1945. These untreated fabrics were manufactured by a variety of mills and represent the production of a cross section of the duck industry at that time. The specific finishing composition chosen for discussion consists of the following: chlorinated paraffin, antimony oxide, precipitated yellow iron oxide, lampblack, a modified copper soap fungicide, and precipitated calcium carbonate. This composition makes an olive drab color.

Fifteen years ago very little factual information regarding the weathering properties of cotton duck under controlled conditions of outdoor weather exposure were available. Around that time the Wm. E. Hooper & Sons Co. began making outdoor exposure studies of our treated and untreated cotton duck in Baltimore, Md. and Miami, Fla. (See Figures 1 and 2 respectively). Exposure was made by tacking the fabric specimens on wooden racks facing south at an angle of 45°. The specimens were tested at intervals of three months for a period of one year, by which time severe damage was evident in both the lightweight and heavyweight specimens of untreated duck tested at Miami. Although some studies were continued for four years, the following data are for only a period of one year.

We also found it necessary to find an accelerated weathering test which could be used as a control test for production and as a screening test for formulation development. After considerable investigation we decided to use the National Carbon Company's Type X1A accelerated weathering unit, without filters. We chose 100 hrs. as the duration of the test. Although not a perfect test it has proved to have much practical value over many years, and is the one currently being used by Military Specification MIL-D-10860(QMC) Duck, Cotton; Fire, Weather, and Mildew Resistant [10], and MIL-C-17106 (Ships) Interim Military Specification, Cloth, Cotton, Canvas; Fire, Water, Mildew, and Weather Resistant [8].

Results and Discussion

As will be seen from the following data this 100-hr. accelerated weathering test causes a loss in breaking

TABLE I. COMPARISON OF NATURAL WEATHER EXPOSURE OF TREATED AND UNTREATED 10-OZ. ARMY DUCK IN BALTIMORE, MD. AND MIAMI, FLA. WITH ACCELERATED WEATHERING

	Unexposed	3 mos. Balto. Md.	3 mos. Miami, Fla.	6 mos. Balto. Md.	6 mos. Miami, Fla.	9 mos. Balto. Md.	9 mos. Miami, Fla.	12 mos. Balto. Md.	12 mos. Miami, Fla.	Accelerated weather tests 100 hrs.
Untreated										
Samples exposed	13	13	13	13	13	13	13	13	13	13
Breaking strength										
Warp	241	194	155	175	125	167	84	154	62	74
Filling	136	104	74	98	63	88	44	91	33	54
Water leakage	19 ml.	1721 ml.	2695 ml.	3348 ml.	2924 ml.	4002 ml.	3779 ml.	3888 ml.	4224 ml.	1182 ml.
*Treated Olive Drab Fire Chief**										
Samples exposed	19	19	19	19	19	19	19	19	19	19
Breaking strength										
Warp	277	270	264	262	246	253	225	230	220	228
Filling	160	165	159	165	158	163	142	155	135	145
Water leakage	42 ml.	3 ml.	4 ml.	5 ml.	5 ml.	3 ml.	7 ml.	2 ml.	26 ml.	4 ml.

Military specification, MIL-D-10860—requirements
Breaking strength warp 210 filling 130
Water leakage 50 ml. with 8" column
all specimens tested dry

Accelerated weather tests are as follows:
A. National accelerated weather unit type X1A
B. Sunshine carbons
C. 100 hrs. exposure with filters removed
D. Data based on average of top and bottom positions on rack

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strength of untreated light weight cotton duck approximately as great as that occurring after one year of natural weather exposure in Miami. The accelerated test, of course, does not cause the degradation from microbiological attack that occurs in locations such as Miami. The destructive agent consists solely of an intense source of ultraviolet light from a carbon arc directed against the test specimen, which is wetted with a spray of water once every 2 hrs. during the test.

Table I shows that untreated 10-oz. Army cotton duck is severely damaged by natural weather exposure in Baltimore and Miami, and by the artificial weather of the 100-hr. accelerated test. We have used breaking strength and water leakage to determine the extent of degradation of the exposed fabrics. These tests were made in accordance with paragraph VI entitled, "Breaking Strength Grab Method," and paragraph III, sub-paragraph 5-c-(2), entitled, "Water Permeability Test," of Federal Specification CCC-T-191a [4].

After one year in Baltimore the untreated 10-oz. duck retained 63% of its original breaking strength in the warp direction, and 67% in the filling. The damage in Miami over the same period of exposure was much greater, only 26% of the warp strength and 24% of the filling strength being retained. It is interesting to compare the results of the Florida test on the untreated 10-oz. duck with accelerated weather test results of 31% warp retention of breaking strength and 40% fill retention of breaking strength. However, it should be again pointed out that the accelerated weather degradation is due solely to ultraviolet light in the presence of water and air, while there was present considerable damage from mildew, in addition to the ultraviolet degradation from sunlight, in the Miami exposure.

The water leakage values for the untreated 10-oz. Army duck also demonstrate the destructive effects of natural and accelerated weathering. Although originally highly water resistant, untreated cotton duck soon loses its water resistance when weathered outdoors, and is rendered unfit for many of its intended uses. It is interesting to note that no great difference was found in the water leakage of the 10-oz. untreated duck whether it was exposed in Baltimore or Miami. Both locations caused considerably greater leakage than that resulting from accelerated weathering, although the latter test demonstrates well the loss in water resistance caused by artificial light exposure alone.

In comparison with the above results on the untreated 10-oz. Army duck, Table I shows the corresponding treated fabric results. After one year of exposure in Miami, the Olive Drab Fire Chief treated 10-oz. Army duck had retained 80% of its original warp breaking strength and 84% of its original filling strength. The results in Baltimore, due to the less severe weather conditions there, were slightly higher, showing 83% warp strength retention and 97% filling strength retention. The accelerated weathering results on these same treated specimens show a retention of 82% of the unexposed warp strength and 91% of the original fill strength. The breaking strength of the treated fabric in both directions under all three conditions of test exposure was above that required by specification for the unexposed fabric.

As opposed to the severe loss in water resistance of the untreated fabric under the three test conditions, the corresponding treated 10-oz. Army duck actually was slightly more water resistant than originally, as measured by the hydrostatic test, after one year of exposure in Baltimore and Miami. The leakage of the treated fabric after accelerated weathering was comparable to that of the Baltimore exposure, while the Miami result was slightly higher.

Table II records the results of a study of the performance of no. 6 treated and untreated duck under the same three conditions of test, illustrating the comparable damage of natural and accelerated weathering to a heavier base fabric. These data were obtained from a greater number of samples and represent the average of results obtained from 21 untreated and 27 treated samples exposed outdoors, and from 8 untreated and 27 treated samples subjected to the accelerated weather test. The data for Table I were obtained from the average of the results of tests on 13 untreated samples and 19 treated samples under the three test conditions.

After one year of exposure in Baltimore the untreated no. 6 duck retained 68% of its original warp strength and 75% of its original fill strength. In Miami 20% of the warp strength was retained and 16% of the filling. The accelerated weather results show a retention of 46% of the original warp strength and 60% of the unexposed filling. Although no. 6 duck has a minimum weight requirement of 20.74 oz./sq. yd. as opposed to the 12.29 oz./sq. yd. minimum of the 10-oz. Army duck, it should be noted that the percentage breaking strength retained of the untreated no. 6 duck was less than that of the much

lighter untreated 10-oz. Army duck after one year of exposure in Miami. This indicates that, unless adequately protected by efficient finishing material, heavy weight cotton fabrics are no more durable than lighter weight ones under the severe conditions of outdoor weather exposure. However, the actual breaking strength values of 70 × 42 for the no. 6 untreated duck are slightly higher than those of 62 × 33 for the 10-oz. untreated duck.

If properly protected with effective finishing materials, however, the original strength advantage of the heavier weight material is retained. This is illustrated by the result of one year of exposure in Miami of the no. 6 treated duck when compared with the 10-oz. duck under the same exposure conditions. The breaking strength of 344 × 296 for the treated no. 6 as compared with 220 × 135 for the treated 10 oz. after one year of exposure in Miami compares favorably with the specification requirements of 335 × 250 and 210 × 130 for the corresponding unexposed fabrics.

The Olive Drab Fire Chief treated no. 6 duck retained 88% of its original warp strength and 102% filling strength after one year of exposure in Baltimore, and 84% warp and 100% filling strength after one year of exposure in Miami. The accelerated weather results on the treated no. 6 duck show a retention of 86% of the warp and 104% of the original filling strength. As with the treated lighter weight 10-oz. duck, the treated no. 6 showed strength values above specification requirements for the unexposed fabric, after one year of exposure in both locations and in the accelerated weather test.

The water leakage of the untreated fabrics after one year of outdoor exposure was very great, although the no. 6 did not leak as much as the 10-oz. Army duck. Little difference was noted between the Baltimore and Miami results. The leakage of the accelerated weather untreated fabrics, although high, is not nearly as great as the naturally weathered samples.

The leakage characteristics of both weights of treated duck were very good, the samples leaking less than originally after the duration of the test under all three conditions.

Figures 3, 4, 5, and 6 illustrate the data from Tables I and II and are self-explanatory.

In the finishing system described the binder or vehicle components, although performing their functions of contributing to the fire and mildew resistance of the fabric, would increase rather than retard weather deterioration if used alone. We found early in the tests that fungicides such as copper naphthenate when used alone, although retarding mildew damage, would actually cause the fabric with which it was treated to deteriorate faster when exposed outdoors than the corresponding untreated fabric. This has since been confirmed by others [1, 2]. While the fungicide used in the composition under discussion has not helped to resist degradation of

TABLE II. COMPARISON OF NATURAL WEATHER EXPOSURE OF TREATED AND UNTREATED NO. 6 DUCK IN BALTIMORE, MD. AND MIAMI, FLA. WITH ACCELERATED WEATHERING

	Untreated									
		3 mos.		6 mos.		9 mos.		12 mos.		Accelerated weather tests 100 hrs.
	Unexposed	Balto., Md.	Miami, Fla.	Balto., Md.	Miami, Fla.	Balto., Md.	Miami, Fla.	Balto., Md.	Miami, Fla.	
Samples exposed	21	21	21	21	21	21	21	21	21	8
Breaking strength										
Warp	351	297	265	266	160	247	107	237	70	159
Filling	270	229	187	210	100	205	76	203	42	162
Water leakage	94 ml.	476 ml.	397 ml.	996 ml.	690 ml.	1720 ml.	1560 ml.	1820 ml.	2043 ml.	507 ml.
	Treated Olive Drab Fire Chief *									
Samples exposed	27	27	27	27	27	27	27	27	27	27
Breaking strength										
Warp	412	400	402	400	368	375	357	360	344	355
Filling	295	313	310	312	300	309	300	300	296	302
Water leakage	34 ml.	10 ml.	6 ml.	9 ml.	4 ml.	9 ml.	9 ml.	6 ml.	13 ml.	23 ml.

Military specification, MIL-D-10860—requirements
Breaking strength warp 335 filling 250
Water leakage 50 ml. with 16" column
all specimens tested dry

Accelerated weather tests are as follows:
A. National accelerated weather unit type X1A
B. Sunshine carbons
C. 100 hrs. exposure with filters removed
D. Data based on average of top and bottom positions on rack

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the finished fabric from light sources, it has contributed much to resisting damage from microbiological attack, particularly in the Florida exposures.

Chlorinated paraffin is unstable to exposure to heat and light which causes the release of hydrogen chloride from the compound. When applied alone to untreated duck chlorinated paraffin therefore accelerates the rate of deterioration of the fabric either in accelerated or outdoor weathering.

Therefore, the essential vehicle or binder constituents of the finishing composition contribute to, rather than diminish, weather deterioration of cotton duck.

Having demonstrated that the cotton duck has been protected by the total finishing composition, we conclude that the other ingredients of the finish, namely the yellow iron oxide, lampblack, calcium carbonate, and antimony oxide, have supplied the demonstrated protection from natural and accelerated weathering. These materials act as screening agents, thereby protecting the finish and the underlying fabric from damage from the destructive wave lengths of light.

It is recognized that in addition to the ultraviolet range, the treated fabrics are affected by other bands of solar radiation including both the visible and the infrared bands. However, other observers [13] have concluded that the band of solar radiation in the

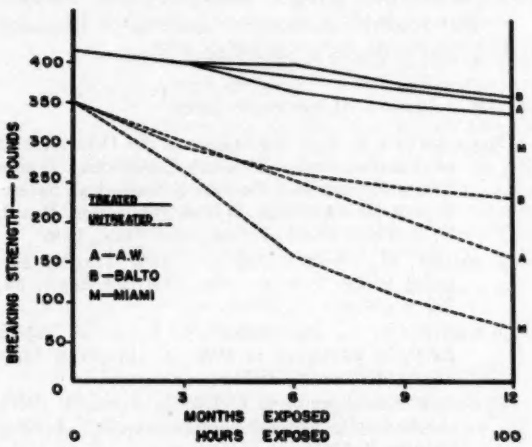

FIG. 3. *Warp deterioration of no. 6 treated and untreated cotton duck exposed outdoors in Baltimore, Md. and Miami, Fla. and in accelerated weathering machine.*

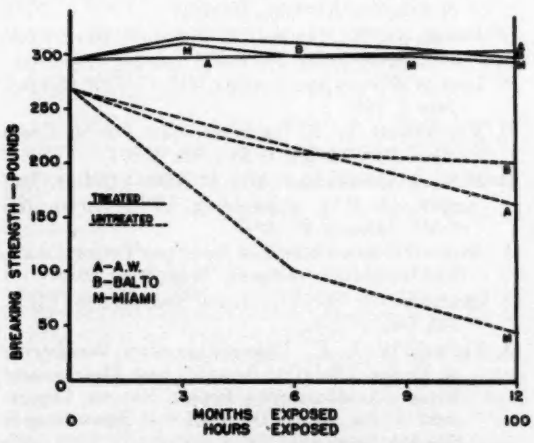

FIG. 4. *Filling deterioration of no. 6 treated and untreated cotton duck exposed outdoors in Baltimore, Md. and Miami, Fla. and in accelerated weathering machine.*

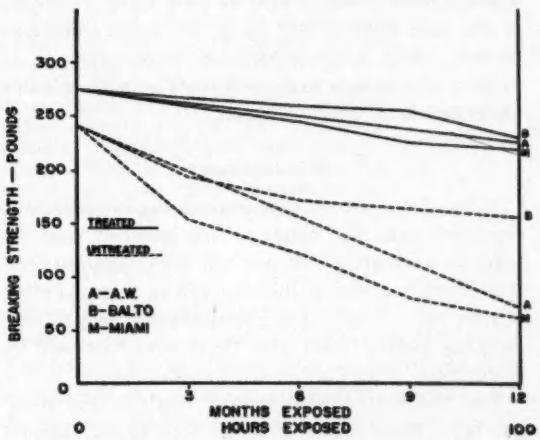

FIG. 5. *Warp deterioration of treated and untreated 10-oz. Army duck exposed outdoors in Baltimore, Md. and Miami, Fla. and in accelerated weathering machine.*

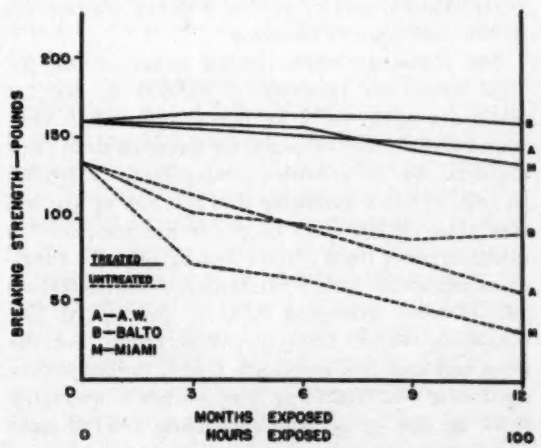

FIG. 6. *Filling deterioration of treated and untreated 10-oz. Army duck exposed outdoors in Baltimore, Md. and Miami, Fla. and in accelerated weathering machine.*

ultraviolet range from 2500 to 3500 Å. units appears to be the most damaging element in the weathering of untreated cotton fabric, when mildew is not taken into consideration.

These destructive wave lengths are effectively "screened out" by the pigment combination of iron oxide, antimony oxide, lampblack, and calcium carbonate. The latter also neutralizes any traces of acid which may occur from decomposition of the chlorinated paraffin.

Other pigment systems have been found to protect cotton equally as well as the olive drab combination under discussion, this color being chosen because of the huge quantities of it which have been produced. Black, white, blue, green, red, yellow, and other color systems have demonstrated at least equal durability to the olive drab system under the same conditions of test. Also other vehicle or binder systems of similar color ranges have performed as well or better under the same test conditions.

Conclusions

It has been shown that untreated cotton duck is rendered unfit for many of its intended uses by outdoor weathering. It has also been demonstrated that effective additive finishing will to a great extent protect and preserve the chemically unchanged, underlying cotton from the degradation caused by weathering.

The accelerated weather test used in this study has been found to be a useful tool in formulation development and production control. However, we do not claim perfect correlation with outdoor exposure results, and recommend that accelerated weathering results always be checked with exposure studies in indicated outdoor locations.

The National Cotton Council estimated that for 1952 there was produced 47,933,000 sq. yds. of fabric averaging 0.752 lb. per sq. yd., which consumed 88,720 bales of cotton for tarpaulin uses. For the same year an estimated production of 23,348,000 sq. yds. of fabric averaging 0.642 lb. per sq. yd. and consuming 36,890 bales of cotton was used for the manufacture of tents. In the awning field, the Council estimated for 1952 a production of 28,429,000 sq. yds. of fabric averaging 0.637 lb. per sq. yd. and consuming 44,570 bales of cotton [11]. For the three end uses this represents a total estimated production of 99,700,000 sq. yds. of fabric averaging 0.677 lb. per sq. yd. and consuming 170,180 bales of cotton.

Cotton duck treated with the type of additive finish described in this discussion has shown a service life in these fields of from five to ten years of constant outdoor exposure [9]. While this would seem to be a reasonable life for such a material, it is possible that some of the newer, chemically modified cottons may enable cotton to give even greater service in these markets. Little is known at the present time of the long term durability of chemically modified cotton finishes such as the partial acetylation process, in use in the paulin, tent, and awning fields.

It has been suggested that combinations of the newer chemical modifications and the older additive type of finishing may best serve cotton in its competition with the synthetic fibers for these markets. Further research is therefore indicated to determine the practical merits of such a possibility.

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The Improvement of Luster of Cotton

Part VII: Fiber Properties and Variety Characteristics in Relation to Luster*

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Abstract

The entire range of American cotton production has been examined for correlation of luster with other fiber properties over two crop years. This has been possible through the cooperation of the Division of Cotton and other Fiber Crops of the Bureau of Plant Industry, U.S.D.A. which provided the yarns and the fiber data.

Luster is shown to be a varietal characteristic, although also influenced by environmental factors. The strongest correlations are of higher luster with greater length, greater strength, and greater roundness. American-Egyptian types, experimental triple hybrids, and Hopi Acala 50 are each different in the relation of fiber properties to luster. All the rest of the cottons, that is, the main Upland group, whether rain grown or irrigated, or long staple, show a uniform general trend of relationships. This trend of relations offers a guide to both spinners and breeders who may wish to select cotton for greater luster. The selections for luster which are possible within the main crop amount to as much gain in luster as can be obtained by plying.

These results are mainly for natural or raw cotton, but the trends remain generally the same after mercerizing, with a tendency for the most lustrous cottons in the natural state to be the ones which gain most on mercerizing.

Introduction

One of the basic phases of the work on improvement of luster of cotton has been the study of the different types of cotton in order, as one objective, to see the range of variation with respect to luster, and, as another objective, to see the possible indications of connection between other fiber properties and luster. Such connections would be of special value to two groups, breeders who are seeking to develop improved varieties of cotton, and spinners who wish to select cotton for the highest luster.

The cotton trade is well aware of certain general connections between cotton types and properties on the one hand, and the degree of luster on the other. In particular, it is generally understood that the longer, rounder, and finer cottons are the best for luster [1, 13, 15] and that mercerizing under tension, which increases the roundness of the individual fiber, increases luster. Buck has raised the question [7], on the basis that mercerizing without tension also increases the roundness, though not the luster, whether some internal structure or molecular orientation factor may not also be involved in luster. Hence a third objective of the study of cotton varieties is to look into the possibility of internal structure effects on luster.

Since mercerizing is almost universally employed in the production of goods in which luster is a factor, it would appear desirable at first thought to base the correlations on mercerized yarns. However, mercerizing has a large effect on all the fiber properties and would itself introduce an additional variable, so most of the correlations studied are those between luster of natural cotton yarn and the fiber properties of the corresponding lint cotton, as ginned. A fortunate factor in this work is that fiber property measurements were available for the gin lint state of the natural cottons used in making the yarns. The material used in this study consisted of yarns from the

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Parts I–VI of this series have appeared in the July 1951, January 1953, and January 1954 issues of TEXTILE RESEARCH JOURNAL. Progress reports on this material have been presented at the Cotton Research Clinics of 1951 and 1952, and at the Gordon Research Conference in 1951.

"Annual Varietal and Environmental Study of Fiber and Spinning Properties of Cottons" of the Division of Cotton and other Fiber Crops of the Bureau of Plant Industry, U.S.D.A. (Abbreviated as B.P.I. in further references). The annual progress reports for the 1949 and 1950 crops [2, 3] give the fiber property data.* These fiber property data were measured at the University of Tennessee Fiber Research Laboratory, except for x-ray data which were obtained at Beltsville. The yarns were spun at the spinning laboratories at Clemson, S. C. and College Station, Texas, and were made available through the cooperation of the Bureau of Plant Industry, and the good offices of Dr. Henry D. Barker and Dr. Thomas Kerr, whose aid and advice have been the key to many problems.

The correlation with mercerizing has been carried out, in part, by mercerizing representative yarns from the whole range of lusters encountered in the natural yarns. The results shown in Figure 1 indicate that in general luster after mercerizing is fairly well correlated with that of the natural yarn. This is in agreement with general opinion and experience [13, 15]. If anything, there is a magnifying factor so that the cotton varieties with higher luster as natural yarns show the greater gain on being mercerized. While this magnifying factor may be the result of a secondary effect, through the lower twist used for the longer cottons, nevertheless the whole general correlation appears valid in a practical sense. To the spinner seeking to buy cotton, the only fiber property data likely to be available are those on the ginned lint, so it is of practical value to put all the correlations on the ginned lint basis.

* X-ray data are not published in the 1950 report but were furnished directly from the Beltsville Laboratory.

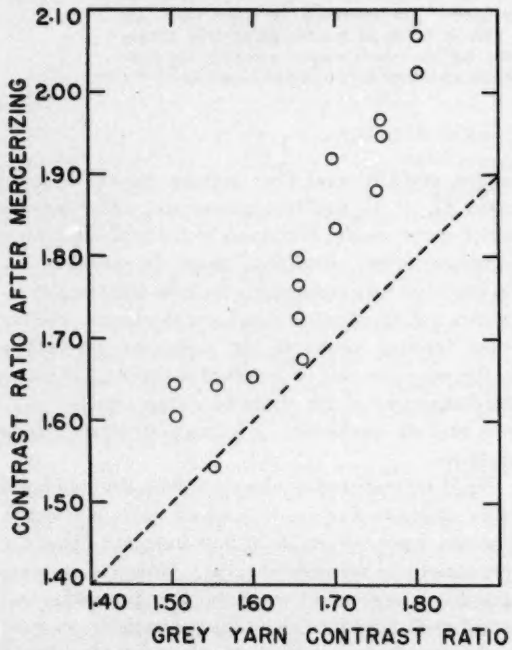

FIG. 1. *Comparison of contrast ratio (used to measure luster) before and after mercerizing, for yarns selected from the 1949 crop to cover the whole range of luster. The broken line indicates one to one correspondence; distance above this line, the gain on mercerizing. This figure shows that the higher the luster or contrast ratio is originally, the greater is the increase with mercerization.*

Throughout this discussion, luster is taken as meaning the property of concentrating reflected light, to greater or lesser degree, near the angle for mirror-like reflection, in opposition to the tendency to be matt, or a diffuse reflector, which scatters light more or less equally in all directions. The numerical measure used for luster is the contrast ratio, discussed more fully in Part I of this series [10]. Contrast ratio is defined as the ratio of the directional reflectance for a mirror angle arrangement, divided by the reflectance or scattering for a representative non-mirror angle. The mirror angle arrangement used is with light and viewing each 45° away from the normal, or line at right angles to the specimen surface, this normal being taken as 0.°. The scattering tendency is represented by having either viewing or lighting at 45°, with lighting or viewing at 0.°. In more mathematical form:

$$\text{contrast ratio} = \frac{45°,\ 45°\ \text{reflectance}}{45°,\ 0°\ \text{reflectance}} = \frac{\text{mirror angle reflectance}}{\text{scattering}}.$$

Results

Luster is a Varietal Property

A variety of cotton can be recognized either from knowing its seed parentage, or by recognizing characteristic combinations of fiber properties and other plant characteristics. All the fiber properties are influenced by environmental factors, which will differ in their impact from season to season and place to place, but certain ranges or combinations of prop-

erties which change together according to a pattern can be called variety characteristics. That luster is a variety characteristic, changing in a given pattern along with other fiber properties, is suggested by the data in Tables I and II, which show the rank in luster of several varieties grown at several locations. Though the numerical value of contrast ratio, by which luster is measured, varies from location to location, the relative rank of varieties with respect to each other is on the whole the same.

That luster is a varietal property is also shown by its season to season correlation, as displayed in Figure 2. In this figure, most of the varieties measured in the two crop yarns, 1949 and 1950, are in the same rank, as indicated by the points falling close to the central trend line, which would run at 45° for perfect correlation.

Differences in Seasons, Measurements, and Methods

The correlation shown in Figure 2 is one of rank. The numerical values of contrast ratio in 1950 fall at a lower level, although with practically the same range from low to high, as those for the 1949 crop. Table III shows that for 44 varieties measured in both years, the 1950 measurements averaged 0.20 unit of contrast ratio lower. The comparisons in Table III suggest that this could be in part a real difference between the general level of the two years, since the difference between systems of winding the yarns can account for only 0.04 unit of contrast ratio, and the difference of systems of measurement for only 0.03 unit more. Whatever the cause of the difference, it has the effect of requiring separate consideration of the correlation of luster and other properties in each of the two years. The results of this separate comparison do indeed show that some

TABLE I. CONSISTENCY OF RANK IN CONTRAST RATIO FOR VARIETIES AT DIFFERENT LOCATIONS (WESTERN GROUP), 1949 CROP

B.P.I. no.	Name	Sacaton, Arizona	State College, New Mexico	Mesa, Arizona	Casa Grande, Arizona
5	Amsak	1.80	1.70		
10	Pima 32	1.78	1.705		
59	Acala × Durango	1.675		1.64	1.61
57	Acala 1517 RB	1.65		1.65	1.60
55	Acala 4–42	1.645	1.58		
62	Paula C	1.575		1.58	1.585
63	Acala P–18–C	1.515		1.525	1.505
Out of rank		0	1	1	0
In rank		7	2	3	4

TABLE II. CONSISTENCY OF RANK IN CONTRAST RATIO FOR VARIETIES GROWN AT DIFFERENT LOCATIONS (EASTERN GROUP). THE VARIETIES ARE LISTED IN ORDER OF THE VARIETY AVERAGE FOR ALL STATIONS, 1949 CROP

B.P.I. no.	Variety	Florence, S. C.	Tifton, Ga.	Jackson, Tenn.	Stoneville, Miss.	Sikeston, Mo.	Clarkedale, Ark.	Auburn, Ala.	Expt., Ga.	Knoxville, Tenn.	Lawrenceburg, Tenn.
31	Wilds	1.645	1.66	1.655							
56	Deltapine 15	1.61		1.61	1.64	1.635	1.74				
118	Cobal T-416	1.65								1.60	1.61
119	Ute 4 C									1.615	1.64
100	Bobshaw 1				1.615	1.61					
120	Mixture 2A									1.615	1.615
126	Pandora	1.63	1.595						1.62		
110	Empire WR	1.62	1.66			1.60		1.59	1.62	1.595	1.605
122	Plains CSS9	1.625	1.605					1.63	1.605		
103	Coker 100W	1.615	1.635	1.57	1.595		1.64	1.625	1.585		
82	Stoneville 2B			1.58	1.615		1.625	1.60			
105	Delfos 9169				1.595		1.62				
62	Paula C				1.605	1.63					
99	Watson Mebane	1.55		1.505							
Out of rank		2	2	1	2	1	0	1	0	1	1
In rank		5	3	4	4	3	4	3	4	3	3

TABLE III. COMPARISONS OF DIFFERENCES, 1949 AND 1950

Comparison	Group of yarns	Average contrast ratio: Fixed angle instrument	Differences	Variable angle instrument
I	44 varieties, crops of 1949 and 1950, B.P.I.	1.652 (1949)		1.455 (1950)
A	Total difference of two years		0.20	
II	12 specimens, Deltapine 15 1949 crop, B.P.I.	1.643		1.614
III	19 specimens, 18 varieties 1949 crop, B.P.I.	1.654		1.616
B	Difference due to instruments		0.03	
IV	1950 winding system 7 layers each 104/in. CP–38C, 36's, 4.0 T.M., 2 specimens			1.42
	1949 Winding system 4 layers each 64/in., same yarn, 2 specimens			1.46
C	Difference due to winding system		0.04	
D	Difference which may be due to real differences in luster $A - B - C = D$		0.13	

TABLE IV. RANGE OF LUSTER IN AMERICAN COTTONS

Crop year	1949	1950
Number of specimens	202	211
Number of varieties or strains *	128	159
Luster (contrast ratio)		
High	1.80	1.70
Low	1.50	1.36
Range	0.30	0.34

* Identified by separate numbers in B.P.I. reports.

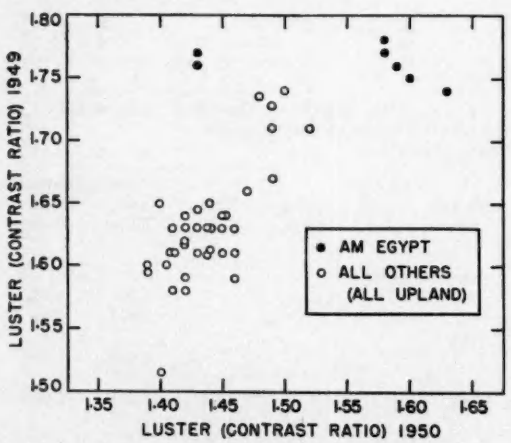

FIG. 2. *Comparison of luster, as measured by contrast ratio, for 44 varieties of cotton measured in two years. Perfect correlation would run along a 45° line, with the scales having a common origin. The origin has been shifted 0.15 unit because of the systematic difference between the two years, but the rank in the two years is in general correlation.*

correlations, notably with x-ray angle, appear to be different in the two years, which supports the view that there may be a real difference of general level of luster from one year to another, just as there are general differences of staple length or strength.

Range of Luster in American Cottons

Table IV shows the similarity of range for the two years examined. The fact that only 44 varieties or strains are common to the two years is less significant than might be thought, since many of both the experimental and commercial strains are essentially similar, and can be grouped into a few broad classes.

Figure 3 shows, for the 1949 crop, the range in two or more specimens of a variety in comparison with the whole range of the crop. This figure indicates the tendency for most of the commercial Upland varieties to fall in a central region. It also shows, as would be expected, that where more specimens were examined of a given variety, each specimen from a different location, the range widened. However, for most of the varieties one can see that there is a characteristic location within the general range.

The range of the whole crop is wider than that of any one type, since it runs from the obsolete variety P-18-C, the low of 1949, and nearly the low of 1950, to the best American-Egyptian and Sea Island types. However, this range does not include unimproved

short staple cottons of either year, nor does it include Asiatic cottons which are shorter and coarser, and may run lower in luster. This type of cotton is not used in practice where luster is desired, however, so the experimental material does cover the whole range of medium and long staple cottons in which luster is a practical factor.

Effect of Twist Correction on Range

Twist has an effect on luster, but is not directly a fiber property. The B.P.I. series were spun as warp yarns, for maximum strength in relation to staple length, on the basis of a standard table of twist multipliers for standard ranges of Upper Half Mean length (U.H.M.) as determined by Fibrograph. This is the standard series of twists used by the P.M.A. spinning laboratories [4]. The range of twist multipliers was from 3.50 to 4.20. Part VI of this series [9] showed that over this range the luster increases, as a round figure, 0.06 unit of contrast ratio per unit change of twist multiplier. This correction has been applied, taking the central twist multiplier (3.80 or 3.85) of each year as a base, so that maximum adjustments of 0.02 unit of contrast ratio were required to correct for twist. The ranges discussed in Table IV and Figure 3 are not corrected, but are as measured and thus are up to 0.04 or so larger than the range of the contrast ratios used for correlation with individual fiber properties.

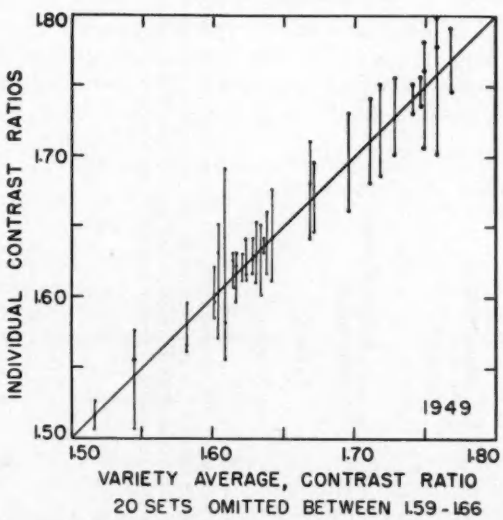

FIG. 3. *Range of luster between specimens of a given variety, grown at more than one location, in comparison with the whole range of the variety averages.*

Groupings of Experimental Material

The Bureau of Plant Industry reports group the cottons into varieties having longer or stronger staple, from which combed as well as carded yarns were made, and the shorter cottons which were studied only as carded yarns. The locations indicate whether the cotton was rain grown or irrigated. This, however, is not a sufficiently fine grained classification and is not based on genetic differences. On the other hand, by no means all of the varieties examined are really different. The fact is that the big commercial varieties are in large part selected to produce as uniform a type of cotton as possible. The chief varieties of commerce do not make up as large a proportion of the B.P.I. sampling as of the crop, but are represented; the B.P.I. series has the advantage of including experimental or breeder's lots, and practically all varieties available, which might be used where high luster is a factor, as well as all locations where cotton is grown. The fact that the B.P.I. series is heavy in long staple cottons makes it especially valuable for studying correlations with luster.

With the advice of Dr. Thomas Kerr of the B.P.I., the varieties have been grouped in 10 classes, as shown in Table V. The basis of classification is indicated by the letters *G* for genetic relationship, *C* for cultivation conditions, that is, rain grown *versus* irrigated, and *L* for length, that is, whether suitable for combing, or only for carding. The length basis is less fundamental than the others, except for extra long or short staple.

All of the measurements used for correlations were made on carded yarns, 36/1. For the longer cottons of Table I of the B.P.I. report for 1950, combed 36/1 and 36/2 yarns were also examined. The results on combed yarns were in general closely parallel to the carded yarn results, so do not require separate correlation.

Explanation of groupings.—Much of the basis of the groupings in Table V will be self-evident, but it should be noted that we are indebted to Dr. Kerr's detailed knowledge of the breeding program to know the groupings of some of the varieties, since the name or number designations are not all self-explanatory.

The American-Egyptian class can be identified in the B.P.I. tables by roller ginning, and by numerical

TABLE V. AVERAGE LUSTER AND FIBER DATA FOR GROUPS OF TYPES OF COTTON *

Group no.	Basis: genetic cultivation length			Group designation	Cultivation	No. in group	Crop year	Luster: contrast ratio	Length U.H.M. in.	Strength: Pressley Index	X-ray angle degrees	Specific surface mm.²/mm.³	Immaturity value *D* mm.²/mm.³
	G		*L*	*Special Cottons*									
1	*G*	*C*	*L*	American-Egyptian	Irrig.	20	49	1.73	1.44	9.14	32.6	481	
						28	50	1.59	1.39	9.46	30.1	494	29
1*a*				Karnak, Egyptian grown	Irrig.	1	49	1.76	1.35	8.73	28.2	504	
						1	50	1.57	1.37	8.7	30.9	484	22
2	*G*			Sea Island	Rain	3	50	1.47	1.50†	8.80	29.7	471	30
3	*G*			Triple hybrids	Rain	10	49	1.71	1.18	9.58	28.0	464	
4	*G*		*L*	Long Staple Upland	Rain	14	49	1.65	1.29	7.47	33.0	473	
						20	50	1.48	1.34	8.03	33.1	527	52
		C		*Western Upland*	Irrig.								
5	*G*			Hopi series		4	49	1.68	1.14	9.08	29.8	428	
						16	50	1.46	1.11	8.74	28.9	434	26
6	*G*			Acala 1517, etc.		35	49	1.63	1.16	7.61	34.3	473	
						51	50	1.44	1.15	7.69	32.8	462	30
7	*G*			P–18–C		3	49	1.51	1.07	6.76	40.5	446	
						3	50	1.41	1.10	6.30	40.5	450	25
		C		*Eastern Upland*	Rain								
8	*G*			Main group		87	49	1.62	1.09	6.78	35.7	463	
						77	50	1.43	1.10	6.73	34.8	464	38
9		*C*		Dryland		18	49	1.62	1.03	7.24	34.3	422	
						15	50	1.43	1.07	6.61	35.0	451	40
10	*G*			Rowden		3	49	1.58	1.03	7.10	35.4	388	
						1	50	1.42	1.07	6.8	34.0	342	18

* All for carded 36's, natural state. The luster is measured by contrast ratio, and has been corrected for the effect of twist by the relation that contrast ratio increases 0.06 for each 1.0 unit decrease in twist multiplier. All corrections were to the most numerous twist multiplier level in each year. Fiber data is from the Bureau of Plant Industries, Division of Cotton and other Fiber Crops.

† Lint was not wholly typical of Sea Island, since crop was raised primarily for seed increase.

classer's grades, as well as by names and locations. The Long Staple Upland includes the varieties Wilds, the E H series, and the "Sealand" series. We are told that these all have the Upland habit of growth, when seen in the field. In addition, three strains designated Sea Island, and having Sea Island growth habit, are included in the 1950 crop, even though the lint produced in that year was not wholly typical of Sea Island.

The Hopi series is based on *AHA* (Acala Hopi Acala)6-1-4, renamed Hopi Acala 50, and its close relatives. The Acala series, consisting of the Acala 1517, Mesilla Acala, and Acala 4-42 groups, are different from the Hopi group, we were informed. The P-18-C represents the old type of western cotton now little grown.

The Eastern Upland rain grown main group constitutes the present improved representatives of typical American or Upland cotton, as known before the extensive growth of cotton under irrigation in the far west. Typical of this group are Deltapine, Stoneville 2B, Coker 100 Wilt, Empire, Mebane, and the like. Rowden and its relatives are set apart by extra thick wall. The triple hybrids are a mixed group of dominantly Upland type, purely experimental. The "dryland" group are regular Upland varieties, subject to some selection and grown in Texas and Oklahoma without aid of irrigation. All the specimens grown at Chickasha, Oklahoma and at Greenville and Chillicothe, Texas were grouped as "dryland." We are informed that the staple length in "dryland" tends to run shorter than for the same varieties grown with more rain, but this relation varies from year to year. In 1950 the "dryland" group showed a very narrow range of luster, although the range of other properties was almost as large as that of the main rain grown Upland group. The narrowness of luster, however, prevents any significant correlation, so charts for this group in 1950 are omitted. Certain smaller groups, eastern cottons grown under irrigation, and western grown in the east, are also omitted from the charts and from Table V.

Trends between and within groups.—Four of these groups are sufficiently well represented and sufficiently distinct to warrant calculation of correlation coefficients within groups in both years. These are presented in Table VI. It is believed that the parallel cases of the Triple Hybrid group in 1949 and the Hopi Acala group in 1950 will be sufficiently clear from the charts without calculation of correlation coefficients, at least for purposes of general comparison. The numerical averages for the properties are shown in Table V. Graphs showing the trends or lack of trends have been prepared, using a uniform scale for all the groups of a given year. Graphs for 1949 are presented in Figures 4 to 7, and for 1950 in Figures 8 to 12. In this series of charts, Figures 4 through 12, the *A* chart for each pairing of properties shows the group averages and indicates the statistical concentration by cross lines extending in each direction, a distance corresponding to one standard deviation, for each major group. The other charts show the individual points for the several groups. Detailed numerical data are not tabulated in this paper, but are on file and available through the Southern Regional Research Laboratory.

TABLE VI. CORRELATION BETWEEN LUSTER AND OTHER FIBER PROPERTIES, WITHIN GROUPS OF SIMILAR VARIETIES OF COTTON REPRESENTED IN TWO CROP YEARS

Group no.*	Group designation	Crop year	Specimens	Correlation coefficient between luster (contrast ratio) and: Length U.H.M.	Strength: Pressley Index	X-ray angle	Specific surface	Immaturity value *D*
1	American-Egyptian	49	20	−.06	.68	−.67	.03	—
		50	28	−.20	.12	−.01	−.07	−.12
4	Long Staple Upland	49	14	.37	.72	−.61	−.12	—
		50	20	.22	.03	.14	−.16	−.06
6	Acala 1517, Mesilla, 4–42	49	35	−.13	.51	−.59	−.38	—
		50	51	−.32	.20	−.62	−.42	−.40
8	Eastern Upland main group	49	87	.28	.38	−.30	−.51	—
		50	77	−.09	.23	−.18	−.47	−.32

* As in Table V.

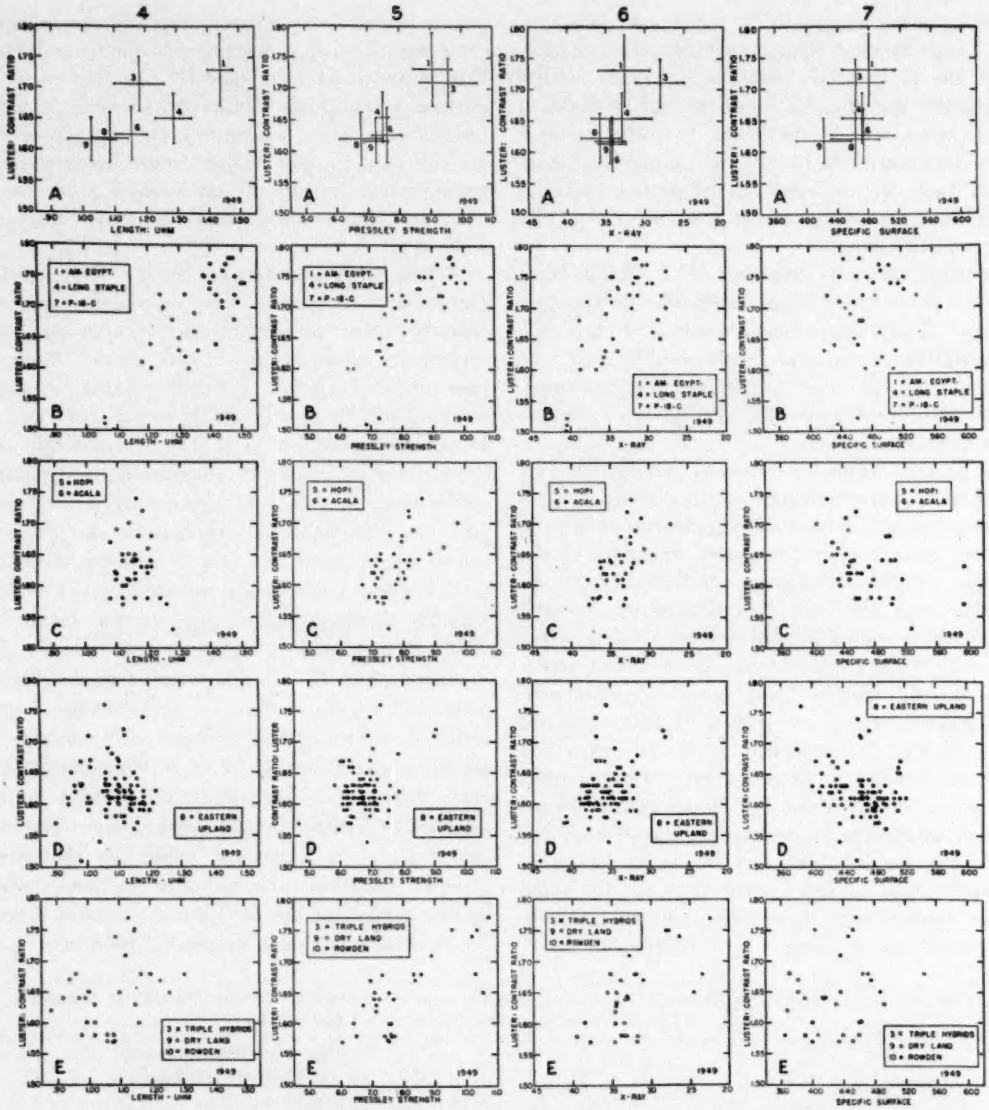

FIG. 4. A—*Length and luster, group averages, 1949 crop. The statistical concentration is indicated by cross arms extending plus or minus one standard deviation. Groups are numbered to correspond to Table V. Length is Fibrograph Upper Half Mean.* B—*American-Egyptian, Long Staple Upland, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.* E—*Triple hybrids, dry land group, and Rowden.*

FIG. 5. A—*Strength and luster, group averages, 1949. Strength is indicated by Pressley Index, which, multiplied by a factor on the order of 10, gives strength in 1000 pounds per square inch.* B—*American-Egyptian, Long Staple Upland, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.* E—*Triple hybrids, dry land group, and Rowden.*

FIG. 6. A—*X-ray angle and luster, group averages, 1949. Note that the x-ray angle scale (horizontal) is reversed in direction, in order that correlation lines shall slant upwards to the right, as in the correlation with strength.* B—*American-Egyptian, Long Staple Upland, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.* E—*Triple hybrids, dry landgroup, and Rowden.*

FIG. 7. A—*Specific surface and luster, group averages, 1949 crop. Arealometer measurements.* B—*American-Egyptian, Long Staple Upland, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.* E—*Triple hybrids, dry land group, and Rowden.*

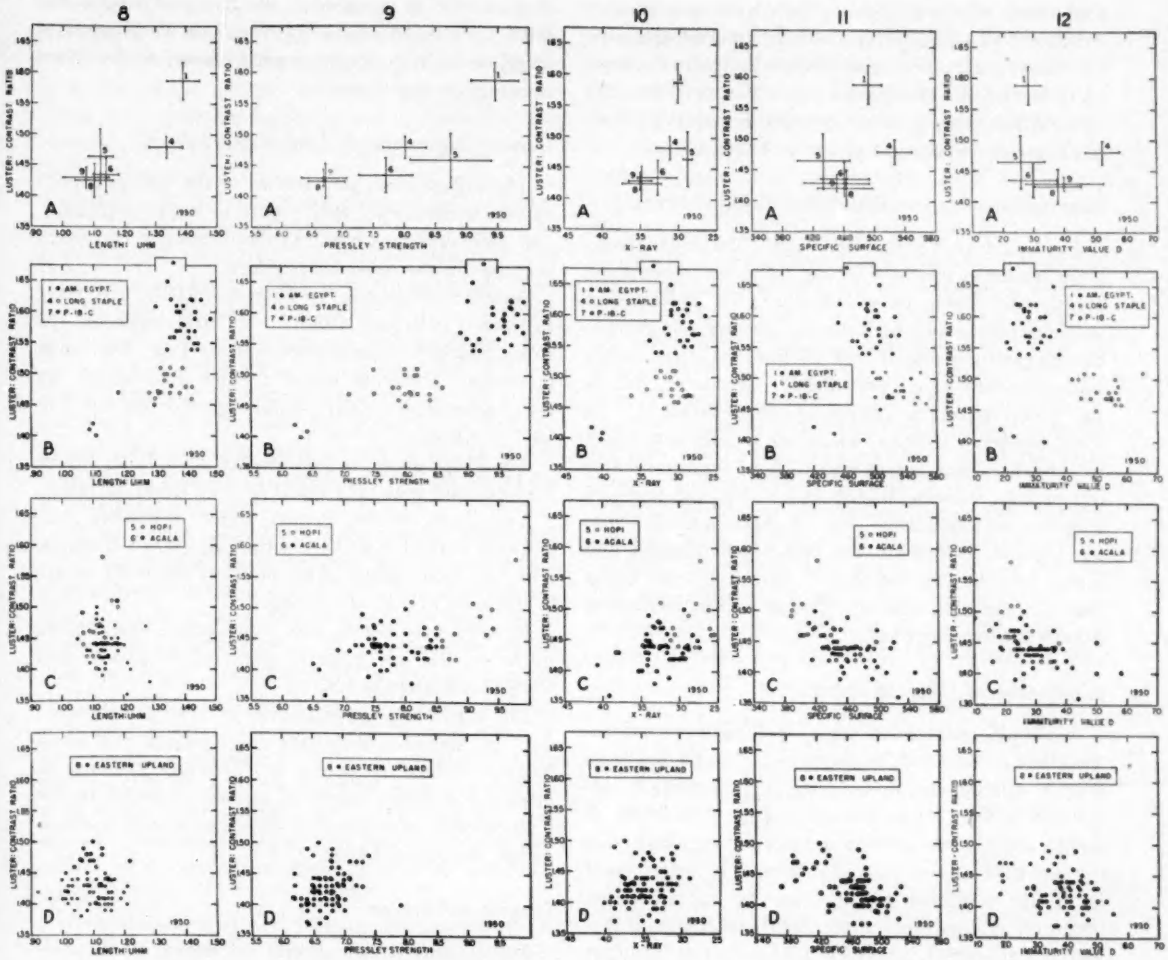

FIG. 8. A—*1950 crop, length and luster, group averages. Cross arms indicate plus or minus one standard deviation.* B—*American-Egyptian, Long Staple Upland, Sea Island, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.*

FIG. 9. A—*1950 crop, strength and luster, group averages.* B—*American-Egyptian, Long Staple Upland, Sea Island, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.*

FIG. 10. A—*1950 crop, x-ray and luster, group averages.* B—*American-Egyptian, Long Staple Upland, Sea Island, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.*

FIG. 11. A—*1950 crop, specific surface and luster, group averages. Arealometer measurements.* B—*American-Egyptian, Long Staple Upland, Sea Island, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.*

FIG. 12. A—*1950 crop, immaturity value* D *and luster, group averages.* D *indicates departure from roundness, by change of Arealometer measurement of specific surface with increased compression of the fiber mass.* B—*American-Egyptian, Long Staple Upland, Sea Island, and P-18-C.* C—*Hopi series and Acala series.* D—*Upland rain grown main group.*

The discussions of correlations of fiber properties and luster which follow are based on two lines of evidence: (*1*) The trend of the group averages (the *A* charts). (*2*) The trends within individual groups, as shown by the other charts under Figures 4 through 12, and the coefficients of correlation within the four main groups which are given in Table VI.

Correlation of Luster with Fiber Length

Figures 4 and 8, for 1949 and 1950 respectively, show, in the *A* charts, a strong trend for increases in length and luster to go together, for averages of major groups. For both years, however, the American-Egyptian group is out of line with the rather uniform trend of all the others. Moreover, this is the group which is genetically most different. In 1949, the triple hybrids, which are a deliberate effort to introduce new genes into Upland types, are also out of line, showing higher luster than the trend of length would indicate. The *A* chart indicates that, for Upland cottons on the broad view, length and luster are linked together. However, the other charts show that the correlation within individual groups is distinctly weak.

Elimination of Effect of Twist

It should be recalled that for these correlations, the effect of twist, which depends on length, has been largely eliminated by applying the correction developed in Part VI of this series [9]. The effect of length still shown here is a basic or residual one; the fact that for the Upland cottons it is rather small is in line with the findings on the special series prepared by Mr. Fiori of the Southern Regional Research Laboratory, in which 1.49-in. cotton was cut to give 1.38 and 1.00 in. U.H.M., and showed only 0.02 units of contrast ratio decrease [9]. The rate of increase from the average of the main group of rain grown cottons to the Long Staple Uplands is 0.03 for 0.20 or 0.05 for 0.28 in., in 1949 and 1950 respectively, a faster rate of change than in the experimentally cut series, but not out of the same range of magnitude. The differences within the experimentally cut series may have been reduced by the effect of the increase in very short fibers as a result of cutting, so that these two sets of data are in general harmony.

In practice the twist is lowered for the longer cottons, so that length has a double action on luster, each effect being in the same direction. When change of yarn size is considered, the fact that longer and finer cottons are used for finer yarns gives fiber length even more leverage with respect to the luster of cotton in trade practice.

Variety Differences in Length and Luster

The differences characteristic of the variety groups may be summarized, with regard to length and luster, and will serve as a guide to the discussion of variety relations in the other correlations:

American-Egyptian is longest (1949) and most lustrous (1949 and 1950). In 1950, however, the Long Staple Uplands were equally long, but lower in luster. Evidently other factors than length set the American-Egyptian strains apart from the Upland varieties.

The Hopi group is just shorter than Long Staple Upland, and generally equal or just lower in luster.

The Acala series, grown under irrigation, correspond to the longer half of the rain grown Uplands. The "dryland" group correspond to the lower center of the main rain grown group.

Rowden may not be well represented, but appears to be on the low edge of the Upland group, and P-18-C is definitely low.

The triple hybrids examined in 1949 are interesting, in showing unusually high luster for their length. These represent a deliberate attempt to introduce a wider range of genetic factors into the Upland type, in contrast to the procedure of selection within the general type.

Length and Luster

Correlations within groups.—Turning to the correlation within groups, the charts of Figures 4 and 8 and Table VI show that the correlation within a group is low, in comparison with the variations which may be arising from other causes. More elaborate statistical study might reveal an underlying correlation within the groups, but from a simple one variable at a time point of view the correlation of luster with length within groups is not impressive, in spite of the strong trend through the entire range.

Correlation of luster with fiber strength.—Figures 5 and 9 show this correlation. The trend in luster is more uniform, over-all, or considering American-Egyptian, triple hybrid, and Upland cottons together, and less uniform, considering Upland groups only,

than was the trend with length. Within each group, however, the trend of correlation is very much stronger than it was for length, especially in 1949.

The differences between variety groups follow a generally similar pattern to that for length. Hopi Acala 50, it may be noted, is more outstanding for strength than for length, but the strength appears to be contributing to luster.

Correlation of luster with x-ray angle.—Figures 6 and 10 display the relation with x-ray angle. As with strength, the trends are more clear cut and impressive in 1949. This is not surprising, since Sisson [16], Berkley [5, 6], Conrad [8], Meredith [14], and others have shown and confirmed that there is a strong correlation between strength and x-ray angle. It should be noted that in the charts the x-ray angles decrease to the right, so that the line of correlation or regression could appear to rise from lower left-hand to upper right-hand as in the preceeding correlations.

X-ray angle and convolution angle.—Meredith [14] has raised an interesting alternative to the correlation of strength with x-ray angle, in proposing that all cottons have nearly the same basic spiral angle, while the expanded fiber is growing in the boll, but owing to differences in fineness, on the development of convolutions as the cotton hairs dry out and collapse, there arise differences of convolution angle. This will be returned to in discussing the possible evidence for internal structure factors, with which both strength and x-ray angle are connected. Meredith's suggestion also raises the possibility of an interaction between fineness and x-ray angle.

Correlations of luster with specific surface.—The measure of fineness used in the B.P.I. series is specific surface, as determined by the Arealometer developed by Hertel [11]. The unit of measurement is square millimeters effective external surface, as measured by air flow, divided by cubic millimeters of solid material of average density, taken as 1.52 for cotton cellulose [3].

Figures 7 and 11 present the data. The trend between groups is far from clear; evidently other factors are more important. Curiously, within the larger groups there appears to be a negative correlation of specific surface with luster, which is the opposite of the rather weak trend suggested by comparison of the main Upland groups. This set of trends is more marked in 1950.

Correlation with immaturity value D.—The property, immaturity value, designated *D*, was made available in the B.P.I. reports for the first time in connection with the 1950 crop. It is described in a recent publication by Hertel and Craven [12]. Briefly, it is the difference in apparent specific surface, when measured by resistance to air flow, at two standard degrees of compression of the fiber mass. The more nearly round the fibers, the less the change of resistance to air flow, and the lower the difference, *D*. *D* could be thought of as a measure of departure from roundness, or as a measure of axial difference.

The relation of luster to *D* is presented in Figure 12, which shows the same general features as the relation with specific surface, shown in Figure 11. The American-Egyptian, Long Staple Upland, and Hopi groups have a more distinct position, however, in respect to *D*, and are clearly out of line with the group to group trend of the other groups.

An inter-relation between specific surface and immaturity value *D* is quite likely. Figure 13, which is plotted from Table 1a of the B.P.I. report for 1950 [3], shows that there is a strong correlation between low specific surface and low immaturity value. If high luster and low *D*, that is, low departure from

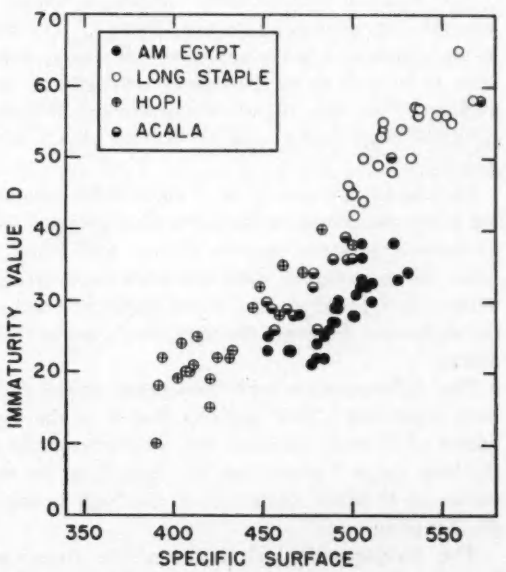

FIG. 13. *Relation between specific surface and immaturity value* D. *Data from Bureau of Plant Industry, Division of Cotton and other Fiber Crops, Report on 1950 crop.*

circularity, are connected, as there is every reason to believe would be the case, the correlation of luster with low specific surface would be indirect, and weaker. Moreover, high specific surface can arise either from fineness, as it largely does with the Egyptian type cottons, or from departure from circularity, as it tends to with the Long Staple Uplands. This would weaken the correlation with specific surface in the range of higher specific surface, though retaining the correlation with *D*.

Discussion

Use of Fiber Properties to Predict Luster

In order to predict luster from fiber properties the correlation among widely differing types and within similar groups should be considered. Taking the broadest differences first, the high luster of American-Egyptian cottons must be explained, since the staple length and twist are the same as for the long staple Upland and Sea Island groups.

Little help is obtained from a study of x-ray angles. In terms of the general average, both the American-Egyptian, the long staple Upland, and the Sea Island are low in x-ray angle, but cover the same range.

The type of differentiation needed is found in strength measurements (Pressley Index). The long staple Upland and Sea Island groups, however, would seem to be well above the average strength, as well as length; but only slightly above average in luster, so some other factor may be holding down these groups.

Specific surface also shows a slight differentiation, but is not consistent, for comparisons of groups. The connection between specific surface and luster is weak, but if continued, the effect seen more strongly within the Upland groups would partly account for the difference between the Egyptian type and the others.

The differentiation with immaturity value, *D*, is more clear cut. This suggests that it is the high values of *D* which decrease the level of contrast of the long staple Upland and Sea Island, or the low values of *D* which contribute to the high luster of the Egyptian types.

The exceptionally high luster of the American-Egyptian appears to come from high length, high strength, and roundness or low *D*; the high *D* of long staple Upland and Sea Island and lower strength decrease their luster. Length cancels out in comparisons of these groups. Among the regular Upland cottons the differences are less striking, but it is here that studies will have the greatest value in aiding selection from the bulk of the crop. One point may be noted, that the Hopi Acala 50 is high among the Upland varieties, including both irrigated and rain grown, and is very high in strength.

These relations between broad groups make it seem reasonable to expect that luster can be predicted at least in part from fiber properties, although further studies of this general type will be required before a prediction formula can be established. The best available practical guide is to choose first for length, second for strength, and third for fineness.

Range of improvement by selection.—If one admits the possibility of buying premium American-Egyptian cotton, the maximum range of improvement possible, from the average of rain grown Upland to the average of the American-Egyptians, is 0.11 to 0.16 units of contrast ratio, in natural cotton yarns, and the range for extremes is 0.30 units. Mercerizing increases the range of improvement. A smaller range, up to 0.05 units of contrast ratio in natural cotton, is available on the average if one goes only to Long Staple Upland. By selecting individual lots, however, one might vary over a range of 0.20 units in the regular rain grown Uplands, or the irrigated Upland varieties grown in the west. Hence it appears that the range of improvement available through selection, even within the common types, is comparable with that available through plying (0.20) as shown in Part VI of this series [9].

Use of luster to select seed cotton for breeding.—One of the practical problems of cotton improvement by breeding is that a means of selection in the seedling row would be desirable, to eliminate the expense of laboratory tests or of increasing to lots large enough for spinning tests. Dr. Kerr tells us that luster seems to be a property which can be judged on small amounts of cotton, and is being examined for this application, in view of the correlations shown by these studies of yarn.

Evidence for Internal Structure

The correlations with strength and x-ray angle at first sight seem to indicate an internal structure factor. Analogous correlations have been found with the luster of drawn and undrawn nylon, but the correlation with low and high stretch rayons from

different producers is not consistent for all producers. The results with man-made fibers may involve other factors, such as the alignment of imperfections to reduce scattering. Meredith's suggestion [14] of a relation with convolution angle suggests that reservations would be in order, regarding internal structure factors, until it can be seen whether the geometrical factor of convolution angle can account for the observed effects. Likewise, the differences between mercerization with and without tension may also involve fiber kinkiness in mercerization without tension.

While the internal-external structure question is still unresolved, the practical value of the correlations of luster with length, strength, and fineness, especially circularity, appears to be on a firm basis of many varieties representing the whole American medium and long staple production, and shows a general year to year consistency.

Acknowledgment

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Book Reviews

ASTM Standards on Textile Materials (With Related Information). Philadelphia, American Society for Testing Materials, Committee D-13 on Textile Materials, 1953. 660 pages. Price, $5.00.

This latest revision (1953) of the well-known D-13 compilation of definitions and terms, methods of testing, tolerances, and specifications brings up to date the additions to "Standards" and "Tentatives" adopted during the past year. Included in the Appendix are chapters which give proposed methods of tests for "fineness" of cotton fibers by resistance to air flow. Detailed procedures together with illustrations of the apparatus and flow diagrams are furnished for the Arealometer and for the Micronaire. These methods are offered for consideration and comments are solicited.

This important reference book can be obtained from the Society whose address is 1916 Race Street, Philadelphia 3, Pa.

World Production of Raw Materials. New York, Royal Institute of International Affairs, Publications Office, 542 Fifth Ave., 1953. 103 pages. Price, $1.50.

This is a completely revised edition of a paper first published in1941. It deals with fibers, natural and synthetic, agricultural products, metals, and nonmetallic minerals. The first 55 pages are devoted to a discussion of the principal raw materials, their uses, sources, geographical distribution, and production trends. The remainder of the book consists of tables which list the principal producing countries, their production of the materials, and percent world production.

Fibres from Synthetic Polymers. Edited by Rowland Hill. Houston, Elsevier Publishing Company, 1953. xv + 554 pages. Price, $12.50.

(Reviewed by Bruno R. Roberts, The Chemstrand Corporation, Decatur, Ala.)

Fibres from Synthetic Polymers may be considered as a source book on most phases between polymerization of the fiber-forming materials and the dyeing performance of the resulting fibers. Following the trend of combining chapters written by various experts in their specific field, the editor has done an excellent job in selecting a list of collaborators, each of them competent and well known for the achievements in his field. The editor must also be credited with writing the first chapter giving in concentrated but well-arranged form an introduction to this treatise on one of the most important technological applications of polymer chemistry.

The book maintains a good balance between fundamental information and engineering data. Since this branch of technology has grown during the last two decades to considerable size, a line had to be drawn on the inclusion of border-line fields. The information on rheological phenomena of spin masses or on certain applications of fiber physics seems somewhat scarce, as main emphasis of most authors rests on chemical and physico-chemical aspects rather than on purely physical approaches. There are several excellent chapters on the fine structure of polymers and fiber crystallinity phenomena, etc., but little on mechanical properties, static, sorption, etc. This statement should in no way detract from the merits of the book, as an objective reviewer must realize the necessity of limiting the scope of a treatise of this kind.

While it is true that fully synthetic fibers are in general not older than 20 years or so, it should be realized that the technology of cellulosic rayons has been in many respects a foundation on which the edifice of the synthetics could be built. There are, however, not too many references to work done before 1930 in the new book. It appears that for a systematic and logical development of the science of synthetic fibers, the relationships to cellulosic rayons could have been stressed to a greater extent. On the other hand, the available space has probably limited the contributors and they chose the way of serving the reader facts rather than showing the development of what until not so long ago was considered an art.

The book comprises twenty chapters dealing with synthesis, polymer structure, spinning, fiber properties, and applications. Polyamides, polyesters, and vinyl and acrylic types are discussed in more detail

while other fiber types (*e.g.*, polyvinyl alcohol, polyurethanes, etc.) are only briefly dealt with in incidental chapters on general aspects. This decision may have been based on relative technological importance and is understandable.

The individual chapters vary slightly in their approach to analogous subjects, but show sufficient coordination to permit easy comparison. For example, the three chapters on the different spinning methods, as the other three chapters on polyamide, polyester, and vinyl-acrylic fibers are arranged in an analogous manner. Particularly the chapter on vinyl and acrylic fibers is outstanding in its completeness and deductive development of the present status of one of the more complex branches of the fiber field.

The editor states in his preface that each chapter is self-contained and can be read without need for referring to accompanying chapters. This arrangement is, in many cases, definitely a great advantage which enables the reader to focus his attention at a given problem without the need of going back and forth in tracing the development of related points. The slight overlapping caused thereby seems to be more than compensated for by the convenient concentration of data.

The book is well printed, contains a wealth of information and many illustrations. It is in general well indexed although various items were found in the text but not included in the subject index. Each chapter has its own references, and the location of the specific reference list is conveniently printed on the bottom of every even-numbered page.

Altogether, *Fibres from Synthetic Polymers* is an excellent reference and text book. It can be highly recommended to those who want to familiarize themselves with the general field as well as to the technologist who needs information on specific points.

Textile Fibers, Yarns, and Fabrics. Ernest R. Kaswell. New York, Reinhold Publishing Corp., 1953. 552 pages. Price, $11.00.

(Reviewed by George Susich, Quartermaster Research and Development Laboratories, Philadelphia, Pa.)

This survey is a comprehensive compilation of our present knowledge of the technical properties of fibers, yarns and fabrics. Although not every aspect of textiles could be covered, those discussed are important from the practical and scientific points of view. The subjects are treated exhaustively and clarify many complex phenomena.

The survey was initiated by the Wool Bureau, Inc., in order to describe the properties of wool and of textile structures made of wool. The original concept was greatly extended by comparing wool with other fibers.

The survey is divided into two parts, describing separately inherent fiber properties and those properties which are more or less modified by the morphology of textile structures. In the first part tensile and transverse properties, friction, response to changes in humidity and temperature, and to other environmental conditions (light, weather, chemicals, microorganisms) are described. In the second part the following complex properties of fabrics are discussed: compressional resilience; thermal, air, and moisture transmission; water repellency; dimensional stability; abrasion and wear; felting and shrinkage; soiling and removal of soil; hand; drape; and luster.

The bibliography comprises 436 references, most of them from 1943 to 1952. This selection is fully justified because the systematic investigation of textile problems is comparatively new.

The author, although himself an expert in many fields of textile research, abundantly uses verbatim quotations from the current textile literature. Thus the reader obtains an illuminating selection of statements in their original form.

Anybody who is called upon to weigh the relative merits of various textile materials is aware of the difficulty encountered in obtaining reliable quantitative data which may serve as a basis for a valid comparison. The author has accomplished this task masterfully in compiling the known facts as seen from different angles. Beside the clarification of complex implications, quantitative data on textiles are the most important assets of the survey. Data are frequently expressed, however, in different units which sometimes makes a direct comparison cumbersome. This situation indicates the necessity for standardization of our methods of expression.

The author is associated with the Fabric Research Laboratories, Inc., Boston, Mass., and his book naturally reflects the philosophy of this outstanding group actively engaged in solving the most difficult problems of textile research.

Cellulose, the Chemical that Grows. William Haynes. Garden City, New York, Doubleday & Co., Inc., 1953. 386 pages. Price, $4.00.

In the words of the author—"The story of cellulose is a good yarn. In the vein of the best scientific fiction (though all factually true) it is enlivened with battling adventure and thrilling whodunit. If you read this volume as a story, you will pick up quite a list of chemistry and economics, just as on an exhilarating tramp through the fields on a sunny October morning you will bring home on your clothes a collection of burs and stickers."

The author whose principal activities today are said to be concerned with raising terriers and writing has had more than a speaking acquaintance with chemistry in many of its ramifications. He is one of the original directors of the Chemical Fund and author of such books as "American Chemical Industry: A History" and "This Chemical Age." Although this reviewer has no knowledge of Mr. Haynes' qualifications concerning the raising of terriers, he can unhesitatingly recommend this book not only as a source of valuable information but also as "a good yarn." Why say more?

Fully-Fashioned Hose Manufacture. S. B. Bradley. Manchester, England, Harlequin Press, 1953. 172 pages. Price, 17s.–6d.

(Reviewed by E. N. Ditton, Gotham Hosiery Company, Inc., New York, N. Y.)

There has been a need for many years for an up-to-date book on full-fashioned manufacture and the current volume will prove a most welcome addition to the all too scant literature on this subject.

The description of the operation of the stitch-forming mechanism as well as of the various types of machines and hosiery constructions is quite complete and clearly described. A few of the terms used are different in this country than in England, but this should present no difficulties.

It is unfortunate in what is otherwise an excellent book that the author has chosen to recommend counting courses per inch "Off" rather than "On" the machine and that no description was given of such course-counting equipment as the Rolande Machine.

It would also have been helpful if some space had been given to length control both on the machine and particularly during the preboarding operation.

This volume should be of value as a text book in textile schools as well as for individuals planning to enter the hosiery industry.

Coarse Cotton Gray Goods—Case Study Data on Productivity and Factory Performance. B. L. S. Report No. 16. New York, 341 Ninth Ave., U. S. Dept. of Labor, Bureau of Labor Statistics, 1953. 106 pages. Gratis.

This report, prepared for the primary use of the Mutual Security Agency by the Bureau of Labor Statistics, will be of principal interest to production managers, superintendents, and method engineers who are concerned with production problems. The information and data used for the case studies were obtained from plant records and plant officials with supplementary information obtained from other government agencies and trade associations. The data covers the different types of gray goods—print goods, sheeting, and duck—produced in 16 selected cotton mills.

The report is divided into three chapters. Chapter I is of general interest and furnishes data on man hours per 1,000 pounds of cotton through the customary manufacturing processes. Thirteen full page illustrations show the several processing operations. Chapter II contains detailed case studies of operations in each plant. Chapter III is a brief discussion of labor policies and relationships in the industry, together with some case studies of labor adjustments to technological changes.

By examining this report plant officials will be able to compare manufacturing operations in their plants with the operations in one or more of the plants in this study.

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